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FEASIBILITY STUDY OF SELF-CONTAINED ENVIRONMENTAL CONTROL UNIT.--ETC(U)
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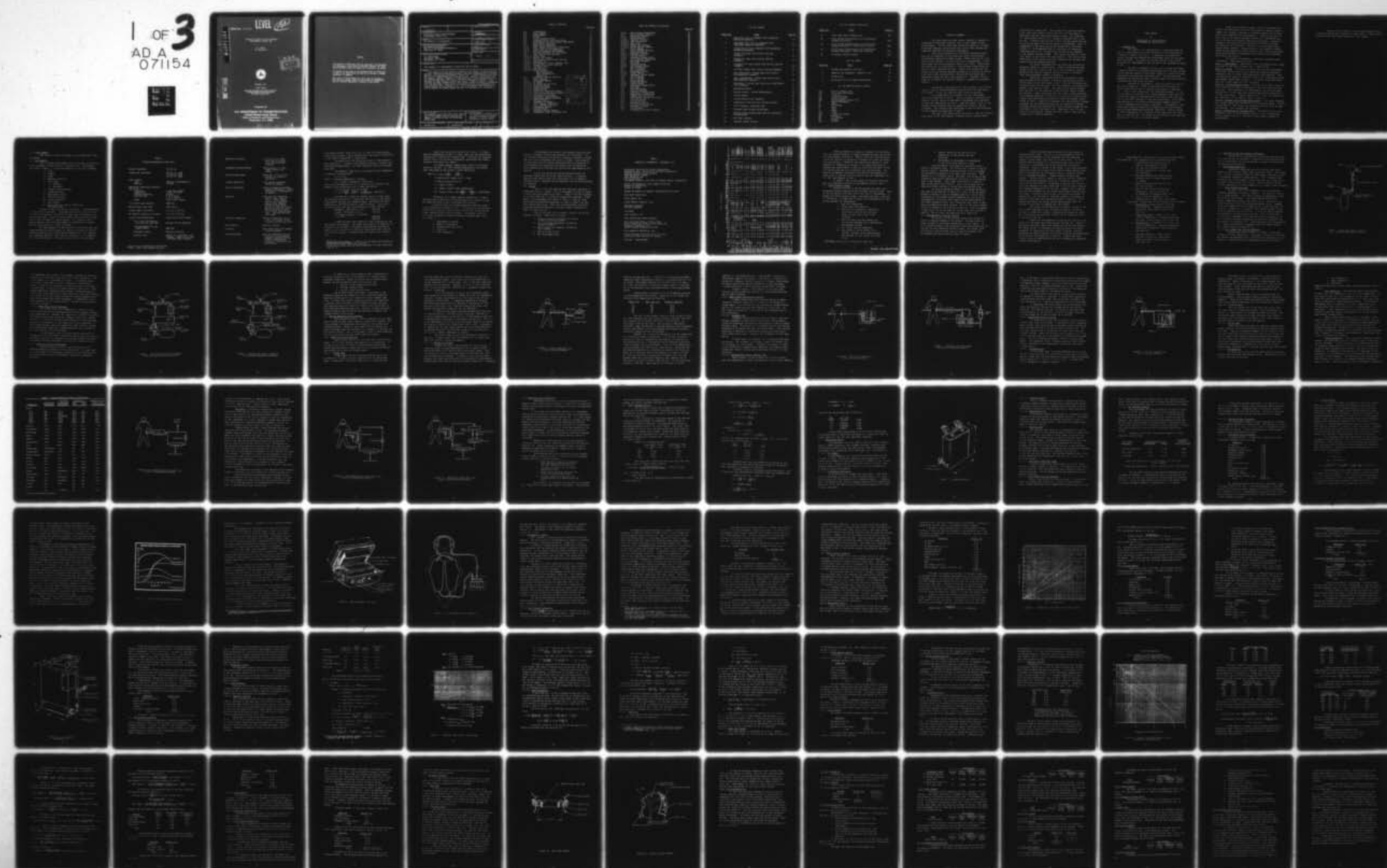

Report No. CG-D-04-79

FEASIBILITY STUDY OF A SELF-CONTAINED ENVIRONMENTAL CONTROL UNIT

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J.W. Maustellar

NOVEMBER 1978

FINAL REPORT

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16. Abstract

This feasibility study pertained to defining requirements, surveying available equipment, devising and evaluating concepts, and making recommendations for development of a self-contained environmental control unit. A modular approach with field replacement is deemed necessary to conserve weight; otherwise, the ECU weight and bulk becomes cumbersome. Adoption of a head/vest water cooled undergarment with ice canisters for heat sinking is advised over use of filtered air cooling. A self-contained rebreather apparatus with a mask inside a protective helmet is recommended as a breathing supply. Both cooling and breathing modules are recommended to be located external to the protective suit. Use of the present POTMC protective suit with the modular ECU concept appears feasible, but evaluation will be required.

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LIST OF ABBREVIATIONS & SYMBOLS

BTU	British Thermal Unit
CFM	Cubic Feet per Minute
cal	calories
CO	carbon monoxide
CO_2	carbon dioxide
ECU	Environmental Control Unit
°F	Degree Fahrenheit
ft	feet
HP	horsepower
hr	hour
k	1000
lb	pound
lit	liter
LPM	liters per minute
min	minutes
mm	millimeters
O_2	oxygen
sec	seconds

EXECUTIVE SUMMARY

The Coast Guard has been given a mandate to respond to discharges of hazardous chemicals into or near waters of the United States. Toxicity and other hazardous properties of these discharged chemicals necessitates that strike team response personnel be supplied with protective equipment.

Coast Guard evaluation of available protective ensembles led to selection of the Protective Outfit Toxicological Microclimate Controlled (POTMC) system. POTMC consists of a protective outer garment, an inner ventilation undergarment, a fishbowl helmet and an environmental control unit (ECU). Respiratory and cooling air are supplied by a filter-blower system using outside air (this comprises the ECU). Recent work showed that the filter could not provide adequate protection or cooling at certain high toxic vapor concentrations, and that the ECU should be a system which does not rely upon outside air. Cryogenic ECU systems are available, but logistic support is deemed to be unsatisfactory.

Accordingly, the objective of this program is to explore state of the art and developmental possibilities for applicable ECU systems. It was not required that an ECU be supplied.

In accomplishing the program, the ECU requirements were first specified in Task I. Task II covered a literature and state of the art survey to determine if equipment were available to meet the requirements of Task I. None was found. Task III considered future research areas by adaption of state of the art equipment. ECU concepts were formulated in Task IV and evaluation of the concepts was performed in Task V.

Few ECU's were found during the survey: none was directly applicable to the requirements, although certain features were

considered for future work. The concept which evolved incorporates a two zone system in which the suit cooling system is separated from the respiratory support system. This provides for considerable flexibility in choosing components and in operations. A modularized ECU with a self-contained rebreather and an ice-cooled water circulating system is recommended. Each is independent of the other and can be resupplied in the field. Further, it is recommended that an alternate soft headpiece, integrated with a full facepiece be provided as an alternate to the present fishbowl helmet. This can be attached to a neck ring, which in turn mates with the ensemble. Thus, the original POTMC need not be altered and either headpiece can be used, depending upon the response required.

The above recommendations are based upon maintaining personnel safety as a prime factor. Other considerations were weight (30-35 lb), service time (2 hr, with resupply), ease of operation and logistic support, and utilization of existing Coast Guard equipment insofar as possible.

Additional investigative work was performed to evaluate the modular ECU concept. A mock-up consisting of an ice-cooled water circulating system, a self contained rebreather and flexible helmet with the butyl suit was assembled and subjectively tested in two one hour tests. This preliminary testing showed that the form, fit and function of the flexible helmet concept was feasible. Water cooling by the "Cool Head" system performed to the degree specified for the unit in relation to capacity, heat removal rate and duration but which is below requirement levels listed in Task I. Mobility of subjects with the externally donned equipment for this modular concept was not adversely affected. Equipment donning and operation was found somewhat impeded by the rigid metal ring of the butyl suit. Otherwise, form, fit and function of the modular concept from this initial study are concluded to be a feasible approach.

FINAL REPORT

on

FEASIBILITY OF SELF CONTAINED ENVIRONMENTAL CONTROL UNIT

1.0 INTRODUCTION

This report is a culmination of a study performed for the U.S. Coast Guard on the feasibility of a self contained environmental control Unit (ECU). It endeavors to present conceptual designs and research and development plans for the Coast Guard to pursue. The objective of this project is to provide direction for improvement in the ECU and is not intended to supply an ECU.

The ECU is intended to allow a fully suited individual to perform tasks in a hazardous environment for a two hour period. The ECU must be capable of providing a means for controlling body temperature and providing respiratory air. The ECU therefore separates the response personnel (strike teams) from any hazardous atmosphere the individual may enter.

Improved ECU equipment is sought to more fully assure personnel protection. POTMC (Protective Outfit Toxiological, Microclimate Controlled) is presently employed as a stop-gap ECU. Since it uses ambient air for respiratory support, it can only be used in a minimum 19.5% oxygen atmosphere and where toxic contaminant types and concentrations are known so that the use time of the XM-41 charcoal filter can be estimated. Since POTMC uses ambient air, the cooling effectiveness depends upon prevailing temperature and humidity conditions. Consequently, lower temperature-humidity conditions increase cooling effectiveness than do higher temperature-humidity conditions. Overall weight of POTMC (protective suit, charcoal filter back pack, and other gear) is about 75 lbs. The weight of the charcoal filter ECU pack comprises 28 1/2 lbs of the total weight.

There are available cryogenic type ECU equipment which satisfy the challenges of hostile environments; however logistic support for cryogenic supplies is a problem because of the Coast Guard strike team mobility requirements. Therefore the goal in this study is to present concepts logistically supportable and easily serviced with present Coast Guard equipment. Weights of cryogenic type ECU packs are comparable with POTMC ECU packs. Any reduction in ECU weight is desirable since personnel work effectiveness improves. Some concepts are considered to reduce weight at the expense of shorter service time; service time being gained back by modular arrangement which permits field replacement during the mission.

This project proceeded by completing succeeding task assignments. These were as follows:

Task I - Requirements. Definition of ECU requirements were listed and given in the Interim Report-Task I, MSAR 77-138.

Task II - Survey. A survey of existing and past ECU developments along with various types of self-contained breathing apparatus information was collected from organizations and agenices. This information was sought to establish if any ECU's particularly meet requirements established in Task I. The survey found that there were not a great number of ECU's available.

Task III - Future Research Areas. From the survey data, future research areas which might be conducted on previous ECU design was evaluated. None completely met requirements; the spin off being consideration of the types and concepts employed to propose ECU's to meet requirements. Interim Report-Tasks II and III, MSAR 78-15, was submitted in fulfillment of Tasks II and III.

Task IV - Propose Units to Meet Requirements. This task presented ECU concepts based upon information of the previous tasks. Priority Listing-Task IV, MSAR 78-42, was prepared proposing units to meet requirements. Four concepts are presented.

Task V - Feasibility of Proposed Units. The feasibility of units proposed in Task IV are evaluated in Task V which is contained in this report (Task VI). The bulk of this report relates to Tasks IV and V.

Study results of Tasks I-IV have been covered in the referenced reports and summarized in this report. Feasibility of proposed units constitutes the bulk of this report.

2.0 STUDY SUMMARY

The results of Tasks I through IV are summarized in the following.

2.1 Requirements

Task I defined requirements which are based upon the contract statement of work and other considerations. Requirements are given in Table 1. Listed requirements include the following:

1. Time
2. Weight
3. Power
4. Ambient conditions
5. Heat loads
   a. Metabolic
   b. Equipment
6. Support and maintenance
7. System pressure
8. Replacement-spares
9. Intrinsic safety
10. Escape capability
11. Odor removal
12. Serviceability (easily cleaned and decontaminated)

A service time of two hours is desired. A maximum height of 30-35 lbs was selected. Subsequent task studies indicate that a 30-35 lb ECU weight is difficult to meet when considering a two hour service time. Since ECU service time directly affects weight, shorter service time will reduce weight. This suggests that a modular design, with field replacement of expendables to extend service time, would be a viable alternate.

The requirements for heat extraction hinge upon heat generated metabolically, by blowers, by chemical canisters to service breathing supplies and by high ambient temperature. For example, the integrated metabolic heat load for the Apollo ECU is 4800 btu for a four-hour period. The cooling capacity for the prototype

TABLE 1

SYSTEM REQUIREMENTS FROM TASK I

Weight (maximum)	30-35 lbs
Dimensions (maximum)	28-1/4 in. high 17-1/8 in. wide 10-1/2 in. deep
Power Supply	
Type	Battery (rechargeable)
Watt-hr	120-200
Operating Conditions (outside the suit)	
Pressure	1 atm (sea level)
Temperature	-40°F to +140°F
Relative Humidity	0-100%
Service Time	2 hr @ 70°F* 1 hr @ 140°F*
Other	Fire, toxic vapors
Total Heat Load Capacity	2400 btu
Maximum Heat Load Rate	1600 btu/hr
Oxygen Supply (minimum)	5.4 scf (0.48 lb)
CO_2 Removal Capacity (minimum)	4.5 scf (0.55 lb)
Support and Maintenance	Logistically serviceable
Task time, maintenance and service, per each	Maximum 30 min downtime
Interchangeability component parts	Required
Component spares	Readily available
Service life	Blower (if required), components, materials of construction 500 hr MTBF**

*Outside suit temperature conditions.
**MTBF = mean time between failure.

Operating Pressure	0.5 to 1.0 in. water positive suit pressure above outside pressure
Expendable Replenishment	Rechargeable in field power supply, air supply
Intrinsically Safe	Required. Will not be source for fire or explosion.
Escape Capability	5-10 minute emergency breathing supply.
Ease of Operation	Quickly donned and doffed. Obvious operation. Little attention or distraction to wearer.
Controls	Indicator for remaining useful time, sensors for air flow, respiratory flow, positive pressure by audible and/or visual signal O_2 signal alert at 19.5%. Manual control to shut off coolant flow to body area. Failsafe malfunction modes.
Umbilical Operation	Valved disconnects, no or little inclusion of surrounding outside suit air.
Odor Removal	Charcoal filter.
Cleaning	Unit compatible with common cleaning agents.
Decontamination	Unit and materials of construction should permit repeated decontamination without compromising structural integrity and performance.

life support pack[1], which uses ice, is 2350 BTU (approximately 2 hour service time), and an average heat load rate of 1200 BTU/hr is the order of magnitude in these packs.

The majority of the system head load is from metabolic heat production. A blower, heat-producing chemical canisters and high ambient temperature (i.e, heat radiation) add to the system heat load.

The metabolic heat load is a function of O_2 consumption as shown by the equation[2]:

$$Q = 5.0\ V_{O_2}$$

where Q = energy expenditure, K cal/min

V_{O_2} = oxygen consumption, liters/min

Using an O_2 consumption of 1.75 cu ft/min (0.83 liter/min) the metabolic heat production rate is about 988 BTU/hr.

$$Q = 5.0\ (0.83) = 4.15\ \text{K cal/min}$$

$$Q = 4.15\ \frac{\text{Kcal}}{\text{min}} \times \frac{60\ \text{min}}{\text{hr}} \times \frac{\text{BTU}}{0.252\ \text{Kcal}} = 988\ \text{BTU/hr}$$

Considering a blower as another source of heat input and consuming 30 watt-hr, it would add 102 BTU/hr to the system. A CO_2 sorber canister will generate heat. Baralyme with heat production of 400 BTU/lb CO_2 will add 110 BTU/hr. Thus, for a two hour period, the total heat produced is about 2400 BTU.

Metabolic, 988 BTU/hr x 2 hr =	1976 BTU
Blower, 102 BTU/hr x 2 hr =	204 BTU
CO_2 sorber canister, 110 BTU/hr x 2 hr =	220 BTU
	2400 BTU

A 2400 BTU heat load capacity is thus selected for the ECU coolant requirement. This head load capacity of 2400 BTU represents 2-1/2 lb water if cooled by vaporization (970 BTU/lb water), 26 lb liquid air if cooled by vaporization (91.7 BTU/lb air) and 16.7 lb ice if cooled by heat of fusion (143.7 BTU/lb ice).

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(1) Damage Control Suit System, N.F. Audet, et al, AD-762428, Navy Clothing and Textile Research Unit, Natick, Mass, May 1973.

(2) Bioenergetics of Space Suits for Lunar Exploration, E.M. Roth, NASA SP-84, 1966, pp. 19.

Heat flow to and from the suit will occur. At lower ambient temperatures of 40°F or lower, heat loss may necessitate throttling or shutting off coolant flow. Provision for stopping coolant flow is an ECU/suit integration requirement but without stopping respiratory air supply.

At higher ambient temperatures, heat will be transferred to the ECU. At 140°F ambient temperature, the radiant heat load added to the system is about 928 BTU/hr.

Where $Q_r = e\sigma A\,[(\frac{T_1}{100})^4 - (\frac{T_2}{100})^4]$

e (emmissivity rubber suit) = 0.86

A (body surface) = 20 sq ft

T_1 = 600°R (140°F)

T_2 = 560°R (∿100°F, body temperature)

$$Q_r = 0.86 \times 0.173 \times 20\,[(\frac{600}{100})^4 - (\frac{560}{100})^4] = 928 \text{ BTU/hr}$$

Therefore, at a higher ambient temperature of 140°F, the heat load on the ECU is increased nearly by a factor of two and operation time at 140°F would be about one hour.

Scenarios that strike team personnel would be likely to encounter were reviewed in Task 1. From time of notification, strike force teams may require up to 5-6 hours to arrive at the scene, depending upon travel distance. The general scope of activities followed by chemical response personnel when called to a scene is:

1. Assessment of hazard
2. Removal of personnel
3. Shutting down the source
4. Clean-up
5. Post inspection

ECU equipment performance requirements hinge upon the various situations strike team personnel will encounter. The most severe situation would be toxic substance poisonous through the skin and an atmosphere deficient in oxygen. Each response occasion will have its unique characteristics and therefore it is not possible to delineate the multiplicity of situations. Some response activities may not require the same degree of protection.

A pick and choose type design approach would let personnel reduce the ECU weight they must bear. A clean-up operation may require that only respiratory air is needed; a protective suit, emergency escape apparatus and cooling apparatus not required.

2.2 Survey

Table 2 lists the agencies and companies contacted in conducting Task II, Survey. Data on equipment is given in Table 3 along with requirements from Task I. Some of the ECU equipment is not available but is listed for comparative purposes. Eight types of ECU equipment are listed in Table 3. Data on other self-contained breathing apparatus is given in Table 3 to provide further background. ECU's are distinguishable from self-contained breathing apparatus since the former incorporate a means for body cooling.

Five of the eight ECU's listed in Table 3 can be considered available. These are as follows:

1. Protective Outfit Toxiological, Microclimate Controlled (POTMC)
2. Self-Contained Atmospheric Protective Ensemble (SCAPE)
3. Modular Omni Environmental Protective Suit (MODTEP)
4. Apollo System (PLSS)
5. EPA Development (ECU)

TABLE 2

AGENCIES & COMPANIES - REFERRAL LIST

Aerotherm, Division of Acurex Corporation
AiResearch Mfg., Division of Garrett Corporation
American Safety Flight Systems
Applied Design Company
Army Research Lab
ARO Corporation
Arrowhead Products, Division of Federal Mogul Corporation

Bendix Instruments & Life Support Division
Biomarine Industries
Bureau of Mines

DuPont de Nemours & Company, Construction Division

East Wind Industries

Fluid Power, Inc.

Globe Safety Products, Inc.

Hamilton Standard
Horizon Research

ILC Dover

Lear Siegler, Inc.

Mine Safety Appliances Company

Navy Clothing Branch, Natick, Mass.
Naval Propellant Plant, Indian Head, Md.
Normalair (Canada), Ltd.
Norton Safety Products Division

Ohio Hygenics Materials, Inc.

Scott Aviation, Division of A-T-O, Inc.
Survivair, Division of U.S. Divers

Willson - Siebe Gorman

Table 3 - Survey Data

Equipment	Weight (lb)	Dimensions LxWxD (in.)	Mounting Position	Power Watts	Pressure	Temp. Range (°F)	Normal Use Time	Fire/Toxic Vapor	Heat Load Cap. Btu	Heat Load Rate Btu/hr	Supply Medium	Breathing Gas: O2 Supply (ft³)	Breathing Gas: CO2 Removal	Breathing Gas: Storage Pressure (psig)	Breathing Gas: Flow Rate (cfm)	Breathing Gas: Flow Type	Breathing Gas: Flow Circuit	Support-Maintenance: Tool Time (min)	Support-Maintenance: Interchange Parts	Support-Maintenance: Spares	Support-Maintenance: Blower Life (hr)	Perm. Oper. Press. (in H2O)	Expendable Replenishment: Field Service	Expendable Replenishment: Power Supply	Expendable Replenishment: Air Supply	Intrin. Safe	Escape Device 5-10 min	Oper's Load	Controls: Air Flow Sensor	Controls: Supply Flow	Controls: O2 Sensor Alarm	Controls: Coolant Diverter	Umbilical	Odor Removal	Other Features & Remarks
Specified	20-35	20-1/4x17-1/2x10-1/2	Back	120-200	1 ATM	-40/140	2 hr	Yes	2400	1000		0.4	0.5	-	-	-	Closed Loop	30	Yes	Yes	800	0.5-1.0	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
SCU Types																																			
PUMC-Microclimate	30	20-3/4x16-1/4x8	Back	60	1 ATM	-40/110	2 hr	OK	-	-	Air	OK	Exhaust	None	10	Air Blower	O.L.	OK	OK	OK	OK	OK	OK	Battery	Amb. Air	-	Yes	OK	-	-	Yes	Yes	Yes	OK	Pack outside suit
SCAPE (Arrowhead)	21	OK	Back	None	1 ATM	-20/120	1-2 hr	OK	-	-	L.Air	OK	Exhaust	-	10-20	Air Blower	S.C.	OK	OK	OK	None	OK	OK	None	Liq. Air	Yes	Yes	OK		Liquid Level		Yes	Yes	OK	Pack inside suit
Apollo (Ham.Std)	60.5	26x17-7/8x10-1/2	Back	240	Space Vacuum	-250/250	4 hr	OK	4000	2000	Comp. O2	11.55	2.7 lb LiOH	400	6-1/2 gpm	Blower Pump	C.L.	-	OK	OK	OK	OK	OK	Battery	LOX	Yes	Yes	OK	-	-	Yes	Yes	Yes	Yes	Pack outside suit
ECDS (Navy Clothing Branch, Battelle)	30.2	20-1/4x10x14	Back	200	1 ATM	-20/140	2-1/4hr	OK	2300	1000	Chemical	OK	Chemical	None	30	Blower	C.L.	30	OK	OK	OK	Slight	-	Battery	OK	Yes	Yes	OK	-	-	Yes	No	No	Yes	Pack inside suit
ERG (Army Research Lab, Battelle)	23	12x11x6 (8x10x3)	Front Back	30	1 ATM	-	3/4 hr	OK	300	300-400	Comp. O2	OK	Chemical	2250	3.6 lpm 1/2 gpm	Water Pump	C.L.	OK	OK	OK	Water Pump	Slight	OK	Battery	O2 Cyl.	Yes	No	-		Low Pressure Alarm		Yes	No	OK	Modular-outside suit, rebreather front, cool head back (development)
PLSS (AiResearch)	16	17x13x6-1/4	Back	None	1 ATM	-	1 hr	OK	1100	450 1200	L.Air	OK	Exhaust	120	10	Evap.	S.C.L.	OK	OK	-	None	Slight	-	None	L.Air	Yes	-	OK		Liquid Level		Yes	Yes	OK	Pack inside suit, no longer manufactured
PLSS (ARO Corp. Firewall Div) P7002004	30	17x12x6-1/4	Back	None	1 ATM	-20/120	1-1/2hr	OK	1150	1150	L.Air	OK	Exhaust	170	10	Evap.	S.C.L.	-	OK	-	None	Slight	-	None	L.Air	Yes	-	OK		Liquid Level		Yes	-	OK	No longer manufactured
PLSS (Litton)	60	10-1/2x17-1/4x6-7/8	Back	None	Space	-	4 hr	-	1000	2000	Comp. O2	-	Exhaust	7500	Demand 1/2gpm	Water Pump	O.L.	-	-	-	None	Slight	-	None	O2 Cyl.	-	Yes	-		Low Pressure Alarm		Yes	-	OK	Prototype Development-Breathing Test
Cryogenic Breathing Apparatus																																			
Firewall Co. Div. of ARO Corp. Model LPO-20LPA-2	37/40	23-3/4x13-1/16x7-9/16	Back	None	1 ATM	-	2 hr	OK	2000	-	L.Air LOX	OK	Exhaust	110	-	Evap.	S.C.L.	-	OK	-	None	Slight	-	None	LOX/L.Air	Yes	No	OK		Liquid Level		-	No	OK	Full Facepiece
Liq.Air/LOX Breathing App. (Bendix Slimline Backpack)	27.7 29.2	10-1/2x14-1/2x6	Back	None	1 ATM	-65/265	2 hr	OK	-	-	L.Air LOX	OK	Exhaust	40-110	-	Evap.	S.C.L.	-	OK	-	None	Slight	-	None	L.Air/LOX	Yes	No	OK		Liquid Level		-	No	OK	Full Facepiece
Aerolox (Seibe-Gorman, Ltd.)	<30	19-1/2x10x6-1/2	Back	None	1 ATM	-	2 hr	OK	-	-	LOX	OK	Chemical	-	-	Evap.	C.L.	-	OK	-	None	Slight	-	None	LOX	Yes	No	OK		Liquid Level		-	No	OK	Full Facepiece
Compressed O2 & Chemical O2 Rebreather																																			
BioPak 60 (Biomarine Ind.)	17	12x11x6	Front	None	1 ATM	32°F& above	3/4hr	OK	-	-	Comp. O2	6.0	3 lb Sodasorb	2250	3.0 lpm	Cont.	C.L.	OK	OK	OK	None	Slight	OK	None	O2 Cyl	Yes	No	OK		Low Pressure Alarm		-	No	None	Full Facepiece [illegible] USCG 160.011/40/9
Proto-Tox SC-22 (Williams Protector-Mosco)	26	-	Back	None	1 ATM	32°F& above	2 hr	OK	Ice cooled	-	Comp. O2	5.5	4-1/2 lb [illegible]	2250	1.5 lpm	Cont.	C.L.	OK	OK	OK	None	Slight	OK	None	O2Cyl	Yes	No	OK		Low Pressure Alarm [illegible]		-	No	None	Full Facepiece USBM 2 hr Ice coolant neck
Also SC-11 (Williams Seibe Gorman)	20	x6	Back	None	1 ATM	32°F& above	1 hr	OK	Chem. Cool. Can.	-	Comp. O2	-	3-1/2 lb Protosorb	2250	-		C.L.	OK	OK	OK	None	Slight	OK	None	O2Cyl	Yes	No	OK		Low Pressure Warning Whistle		-	No	None	Full Facepiece
Scott-Rescue-Pak P/N 900950-00 (Scott Aviation)	25	24x17x7-1/2	Back	None	1 ATM	32°F& above	4 hr	OK	-	-	Comp. O2	16.0	Chemical	1800	1.5 lpm	Cont.	C.L.	OK	OK	OK	None	Slight	OK	None	O2Cyl	Yes	No	OK		Low Pressure Alarm		-	No	None	Full Facepiece USBM/USCG approved
McCaa (MSA) P/N 01-40430	30	23x16x6	Back	None	1 ATM	32°F& above	2 hr	OK	-	-	Comp. O2	8.5	Cardoxide	2265	-	-	C.L.	OK	OK	CE	None	Slight	OK	None	O2Cyl	Yes	No	OK		Low Pressure Alarm		-	No	None	Full Facepiece (also mouthpiece) USBM [illegible]
Chemox P/N 01-07900 (MSA Co.)	13.5	17x16x6	Front	None	1 ATM	-20/150	1 hr	OK	-	-	Chem. O2	8.0	Chemical	0	-	-	C.L.	OK	OK	OK	None	Slight	OK	None	Canister	Yes	No	OK		Timer		-	No	No	Full Facepiece USBM [illegible]
Auer MR 56/400 (Auergesellschaft)	-	-	Back	None	1 ATM	-	4 hr	OK	-	-	Comp. O2	10.3	Chemical	-	1.6 lpm	Cont. (demand)	C.L.	OK	OK	OK	None	Slight	OK	None	O2Cyl	Yes	No	OK		Low Pressure Alarm		-	No	None	Mouthpiece or Oral-Nasal [illegible]
Scott-Draeger D-174	20.5	x6.2	Back	None	1 ATM	-	3/4hr	OK	-	-	Comp. O2	9/14.3	Chemical	[illegible]	-	Cont. (demand)	S.C.	OK	OK	OK	None	Slight	OK	None	O2Cyl	Yes	-			Low Pressure Alarm		-	No	None	
Compressed Gas Breathing Apparatus																																			
Scott Air-Pack IIa P/N 900000-00 (Scott Aviation)	30	x8	Back	None	1 ATM	-25°F& above	30min	OK	-	-	Comp. Air	45 ft³ (air)	Exhaust	2216	As required	demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	No	OK		Low Pressure Alarm		-	No	None	USBM
Scott Air Pak 4.5 P/N 900450-00 (Scott Aviation)	20.7	21-4/8x x8-1/2	Back	None	1 ATM	-25°F& above	30min	OK	-	-	Comp. Air	45 ft³	Exhaust	4500	Up to 300 lpm	demand	O.L.	OK	OK	CE	None	Slight	OK	None	Air Cyl.	Yes	No	OK		Low Pressure Alarm		-	No	None	Full Facepiece - NIOSH/MESA Approved
Scott Pressur-Pak 4.5 P/N 900456-00	20.7	21-4/8x x8-1/2	Back	None	1 ATM	-25°F& above	30min	OK	-	-	Comp. Air	45 ft³	Exhaust	4500	Up to 300 lpm	Press. demand	O.L.	OK	OK	CE	None	Slight	OK	None	Air Cyl.	Yes	No	OK		Low Pressure Alarm		-	No	None	Full Facepiece - NIOSH/MESA Approved
Globe Guardian (Globe Safety Prod)	33	23-3/4x10-1/4x10-3/4	Back	None	1 ATM	-25°F& above	30min	OK	-	-	Comp. Air	45 ft³	Exhaust	2215	As required	Press. demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	No	OK		Low Pressure Alarm		-	No	None	Full Facepiece - NIOSH/MESA Approved
Cobo 770 (Fluid Power, Inc.)	30		Back	None	1 ATM	-25°F& above	30min	OK	-	-	Comp. Air	-	Exhaust	-	As required	Press. demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	No	OK		Low Pressure Alarm		-	No	None	NIOSH/MESA Approval
MSA Firefighter System MSA FES	[illegible]	x8-1/2	Back	None	1 ATM	-25°F& above	30min	OK	-	-	Comp. Air	40/60	Exhaust	4500	As required	Press. demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	No	OK		-		-	No	None	Full Facepiece
MSA Air Mask, demand type P/N 463838 MSA	30	x8	Back	None	1 ATM	-	30min	OK	-	-	Comp. Air	45	Exhaust	2250	As required	demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	No	OK		-		-	No	None	Full Facepiece
MSA Air Mask, Press. demand P/N 463833	30	x8	Back	None	1 ATM	-25°F& above	30min	OK	-	-	Comp. Air	45	Exhaust	2216	As required	demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	No	OK		Low Pressure Alarm		-	No	None	Full Facepiece NIOSH/MESA Approved
Survivair, U.S. Divers Co.	30.5	-	Back	None	1 ATM	-25/200	30min	OK	-	-	Comp. Air	45	Exhaust	2216	As required	Press. demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	No	OK		Low Pressure Alarm		-	No	No	Full Facepiece NIOSH/MESA Approved
Emergency Escape Devices																																			
Escape Flat Pack (Am.Saf.Flight Sys)	<8	Flat Pack	Shoulder Strap	None	1 ATM	-25/200	5min 15min	OK	-	-	Comp. Air	5	Exhaust	5000	-	Cont. Press. demand	O.L.	5	OK	OK	None	Slight	OK	None	Air (Tubes)	Yes	-	-		-		-	-	No	Hood, Full Facepiece Rigid Helmet Options 2nd generation Lear Siegler
Survivair 5 min Emerg.(U.S.Divers)	-	Flat Pack	Back	None	1 ATM	-25/200	5min	OK	-	-	Comp. Air	5	Exhaust	3000	30 lpm	Cont.	O.L.	OK	OK	OK	None	Slight	OK	None	Air Bottle	Yes	-	-		-		-	-	No	Hood with Neck Seal, Throw-away Bottle
SKA-PAC (ESD) Scott Aviation	8	Cylindrical	Hip	None	1 ATM	-25/200	5min	OK	-	-	Comp. Air	6.5	Exhaust	-	As required	Press. demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	-	-		-		-	Yes	No	Oral Nasal or Full Facepiece
Short Snorter (Globe Safety Products)	13	Rectangular [illegible]	Hip	None	1 ATM	-25/200	10min	OK	-	-		10	Exhaust	2215	As required	demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl	Yes	-	-		Low Pressure Alarm		-	Yes	No	Full Facepiece
Escape Mask (MSA)	8	Cylindrical	Hip	None	1 ATM	-25/200	5min	OK	-	-	Comp. Air	6.5	Exhaust	2215	As required	demand	O.L.	OK	OK	OK	None	Slight	OK	None	Air Cyl.	Yes	-	-		-		-	Yes	No	Bite Mouthpiece-Also Air Sling with Full Facepiece & Air-Escape w/Oral-Nasal
Emerg. Escape for USAF-Missile Sites (Bendix)	8.5	-	Back Front	None	1 ATM	-	10min	OK	-	-	[illegible]	1.0	Sodalime	3000	-	3-2 lpm	C.L.	-	-	-	None	Slight	-	None	O2-Air Tank	-	-	-		-		-	-	No	Hood w/Neck Seal (Development)
SCSR (MSA)	3.0	9x5x2-1/2	Front	None	1 ATM	-20/150	10min	OK	-	-	Chem. O2	1.0	[illegible]	0	-	-	C.A.	OK	-	-	None	Slight	OK	None	Canister	Yes	-	OK		-		-	-	No	Bite Mouthpiece Throw-Away Unit USAF
60 min SSR (MSA)	6.5	10-4/8x7-3/4x3-3/4	Front	None	1 ATM	-20/150	1-1/2hr	OK	-	-	Chem. O2	8.0	Chemical	0	-	-	C.A.	OK	-	-	None	Slight	-	None	Canister	Yes	-	OK	Timer	-		-	-	No	Bite Mouthpiece NIOSH/MESA Throwaway App.

SCAPE and MODTEP are based on cryogenic air and therefore unacceptable because of supply problems but meet weight and size requirement constraints. APOLLO (PLSS) ECU requires space vacuum for cooling, is excessive in weight and volume and therefore unacceptable. POTMC has the undesirable feature of using ambient air, rendering it useless in an oxygen deficient atmosphere and questionable in service time since the XM-41 filter life varies with the toxic substance and concentrations. The modular arrangement furnished by the EPA ECU development provides about 35 minutes service time and does not completely fulfill the requirements of Task I.

In summary, the survey showed off-the-shelf ECU hardware not completely satisfying requirements given in Task I.

2.3 Future Research Areas

State of the art in the ECU designs and other self-contained breathing apparatus was provided from the survey. None of the ECU designs entirely fulfill all Task I requirements. A summary of future research areas, concluded from Task I and Task II information, included the following for consideration of proposing concepts for development.

1. Umbilical operation*
2. Vortex tube with umbilical
3. Two-zone suit operation, separating respiratory and cooling functions, either by neck seal or by a full facepiece
4. With the above consider ambient air for cooling purposes only, determining percutaneous hazards
5. Ice cooled vest and headpiece
6. With option 3, using option 5 for cooling, consider suit pressurization with ambient air and highly efficient filter

*Including filter on an inlet end of umbilical.

7. Modular operation and choice of components to fit the threat and the situation
8. Recharging or replacement of expendables in the field while the ECU is worn.

Each ECU design is planned for integration with a specific protective suit. The various ECU's listed in the survey are unique. The POTMC protective butyl suit is arranged to mate with its backpack in an open cycle flow path. Thus, ambient air is filtered, enters the butyl suit by way of the composite ventilation undergarment from which it is exhausted back to the ambient. Other types are primarily closed or semi-closed cycle flow circuits. ECU's are arranged for integration either outside or inside their protective suits.

In view of emergency egress, it is deemed advisable that the ECU be external to the suit so that it may be easily donned or doffed in case of emergency egress or to aid field recharging or replacement without shedding the suit to do so. Consideration is given in this report on the modification of the POTMC protective butyl suit, since the Coast Guard is presently equipped with these outfits. And, in the case of POTMC, the ECU is donned on the outside of the suit. This arrangement is desirable; it can be taken off and be used while driving a vehicle. Not all ECU's reviewed have this capability.

2.4 Proposed Units Priority Listing

The results of the previous three tasks served as a basis to prepare conceptual ECU designs. The feasibility of these concepts is evaluated subsequently in this report. It is of course axiomatic that personnel safety and reliability of the ECU are most important priority items. ECU weight, bulk distribution, service time, ease of operation support and maintenance are other priority items of concern.

Excessive weight reduces personnel effectiveness to perform mission tasks. Ability to do work becomes divided between energy expended to carry equipment and the remaining energy, in that order, available to do useful work. It is important that ECU design be of tolerable weight, bulk and distribution so assignments can be performed with minimum encumbrance. Little is gained if ECU weight is such that personnel experience excessive fatigue within the ECU design service time. Bulk of the ECU must be considered because of passing through 30 inch diameter hatchways. Ladders reduce clearance even further. The ECU profile (depth) is the most critical dimension. Modularizing the components would be a worthwhile approach in achieving minimum profile. Acceptance of shorter unit service time with resupply to extend stay time in the suit would require more frequent manipulation of the ECU. However, with a smaller ECU some rearrangement of the system might permit improved self-servicing. A single larger ECU may not provide this degree of versatility. An individual's complete command of equipment is especailly desirable when emergency egress is required. This remains desirable even though strike team personnel will be working in pairs and can depend upon one another.

Even though strike teams will be highly trained in the use of their equipment, ease of operation remains a prime objective. A simplistic design is preferred and operation should be as obvious as possible with little left to chance for error in the use of the ECU.

Support and maintenance are required for the ECU since design will be based upon reuse and not one time use. Readily and easily available spares and resupplies must be considered in the design as well as compatibility with existing Coast Guard equipment for reservicing the ECU concept selected. Encased components to reduce exposure and to provide easier decontamination are maintenace considerations in the ECU. Support and maintenance tasks are important but are not as immediately demanding as other requirements.

Respiratory air supply and cooling are paramount design considerations. ECU concept priority considerations are:

1. A modularized ECU having priority over an integrated ECU concept
2. Two zone suit operation having priority compared to a single zone suit operation
3. Bottled breathing air supply having priority over a filtered breathing air supply
4. Water cooling having priority over air flow cooling
5. Wet ice sink having priority over ambient air, dry ice, liquid air or mechanical refrigerant heat sink
6. Use a filter or ambient air for breathing only, with water cooled vest.

A priority listing order of ECU concepts are as follows:

1. Modular ECU-1- Water Cooling, Two Zone Suit Operation. Separate respiratory module and water cooling module; dual pack ECU.
2. Single Pack ECU-2 - Water Cooling Two Zone Suit Operation. Combined respiratory and water cooling module; single pack ECU.
3. Modular ECU-3 - Filtered Air Cooling, Two Zone Suit Operation. Separate respiratory module and filtered air cooling module; dual pack ECU.
4. Modified POTMC ECU - Water Cooling, Separate filtered air respiratory module and water cooling module; dual pack ECU.

3.0 RESPIRATORY AND HEAT REMOVAL APPROACHES

The ECU basic functions are to provide respiratory support and cooling for personnel. Discussion on the state-of-the-art of respiratory and cooling devices is given in this section as background information.

3.1 Respiratory Apparatus

Respiratory apparatus can be classified into three types of flow circuits; open, semi-closed and closed. The closed flow circuit is the most effective from weight, duration and profile problems inherent in these devices. This is because the breathing gas is not dumped from the apparatus as is done with an open or semi-closed flow circuit. State-of-the-art of respiratory apparatus available commercially is given in the following.

3.1.1 Open Circuit Apparatus

An open circuit flow schematic of a self-contained breathing apparatus is shown in Figure 1. Gas supply is usually air in these devices. This type of breathing apparatus is used primarily by firefighters. Air (held pressurized at 2200 psig) is supplied by opening the bottle valve. Pressure is reduced to about 70 psig by a pressure reducing valve. A demand or pressure demand valve then supplies air to the mask upon inhalation. Exhaled air is vented to the ambient through a check valve to complete the flow circuit. A 45 cu ft bottle supplies approximately a 30 minute service time. Since a fresh supply of cool air is furnished during each inhalation, the open cycle self-contained breathing apparatus are the most comfortable but are wasteful of breathing air. These apparatus weigh around 30-33 lbs. Recent development in composite material supply bottles has lowered weight to around 24 lbs.

3.1.2 Semi-Closed Flow Circuit Apparatus

Improved gas supply economy is offered by the semi-closed flow circuit apparatus. Lung power is used to recirculate gas through the apparatus which classifies the apparatus as a rebreather. These require more components than an open circuit

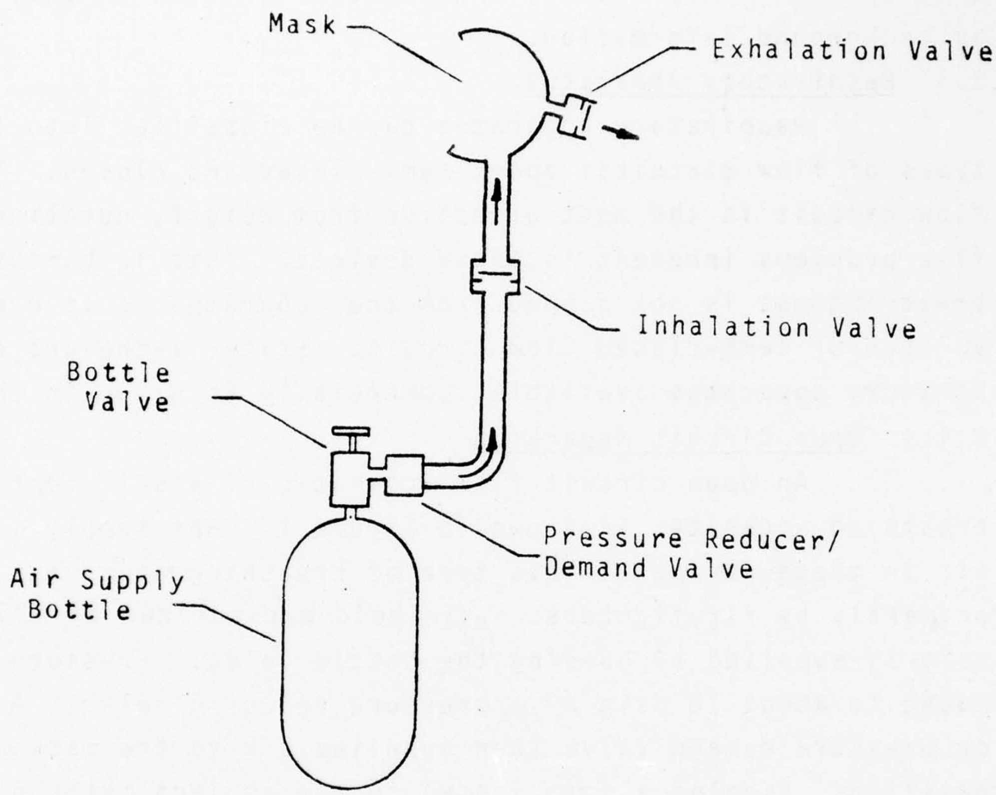

FIGURE 1. OPEN FLOW CIRCUIT SCHEMATIC
SELF-CONTAINED BREATHING APPARATUS

flow apparatus and include a CO_2 scrubber canister and breathing bag which are not used in the open flow circuit apparatus. The flow schematic is illustrated in Figure 2. A constant oxygen flow purge is provided in excess of metabolic requirements. Oxygen is used in the apparatus to prevent buildup of nitrogen if air were used. Excess O_2 is purged through a vent valve. Even though additional components (CO_2 scrubber, breathing bag) are used in the semi-closed flow circuit apparatus the more efficient utilization of the gas supply provides for weight reduction compared to the open flow circuit apparatus. A commercially available apparatus of this type, weighing 17 lbs, has a rated service life of 45 minutes.

3.1.3 <u>Closed Flow Circuit Apparatus</u>

The closed flow circuit apparatus is similar to the semi-closed flow circuit apparatus, having a CO_2 scrubber canister and a breathing bag. Whereas the latter has a constant flow purge, the former provides gas supply by a demand valve or by a demand chemical. A vent valve to dump excess pressure is also provided. Figure 3 is a schematic of the closed flow circuit apparatus. A unit incorporating a potassium superoxide (KO_2) canister (rather than pressurized oxygen and a demand regulator) has a weight of 13 lb and service life of 60 minutes.

The rebreather with its recirculation characteristic is generally less comfortable (thermally) than an open flow circuit apparatus since heat is produced from the CO_2 scrubbing canister. The payback with the rebreather is a savings in weight and bulk.

3.1.4 <u>Positive Pressure Maintenance</u>

Negative pressure occurs in the facepiece of self-contained breathing apparatus during inhalation. If a good seal is not provided by the facepiece, leakage into the facepiece will result and entry of hostile atmospheric gases will jeopardize personnel.

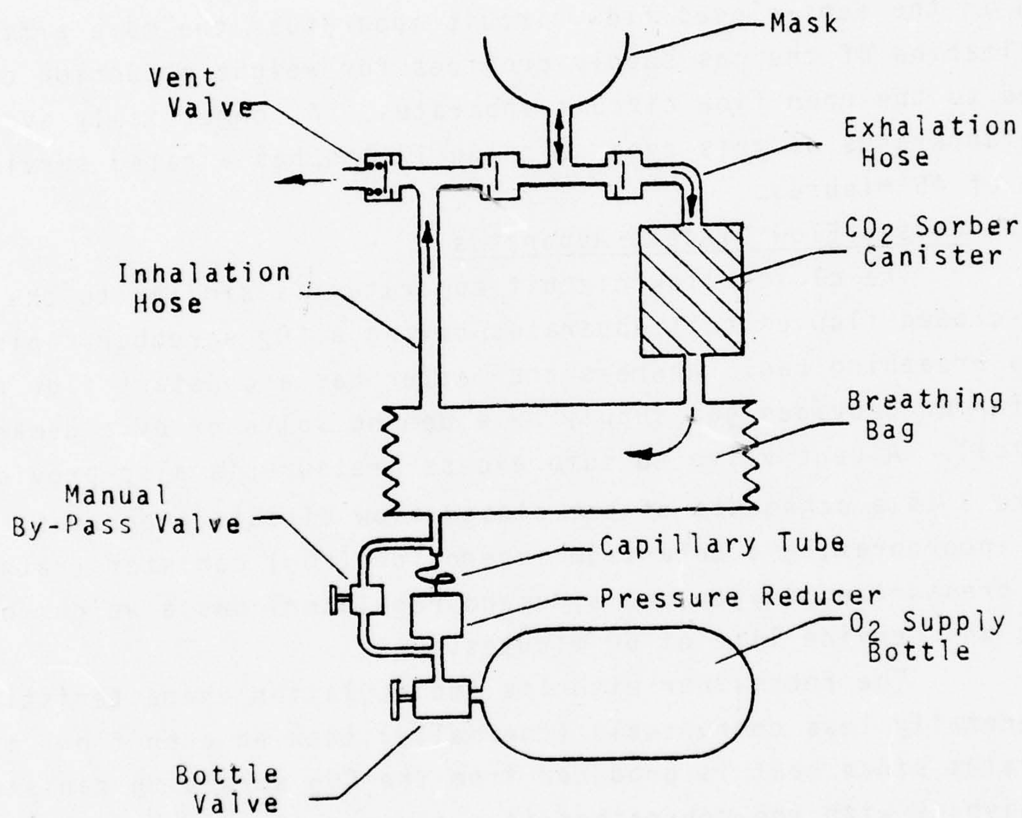

FIGURE 2. SEMI-OPEN FLOW CIRCUIT SCHEMATIC
SELF-CONTAINED BREATHING APPARATUS

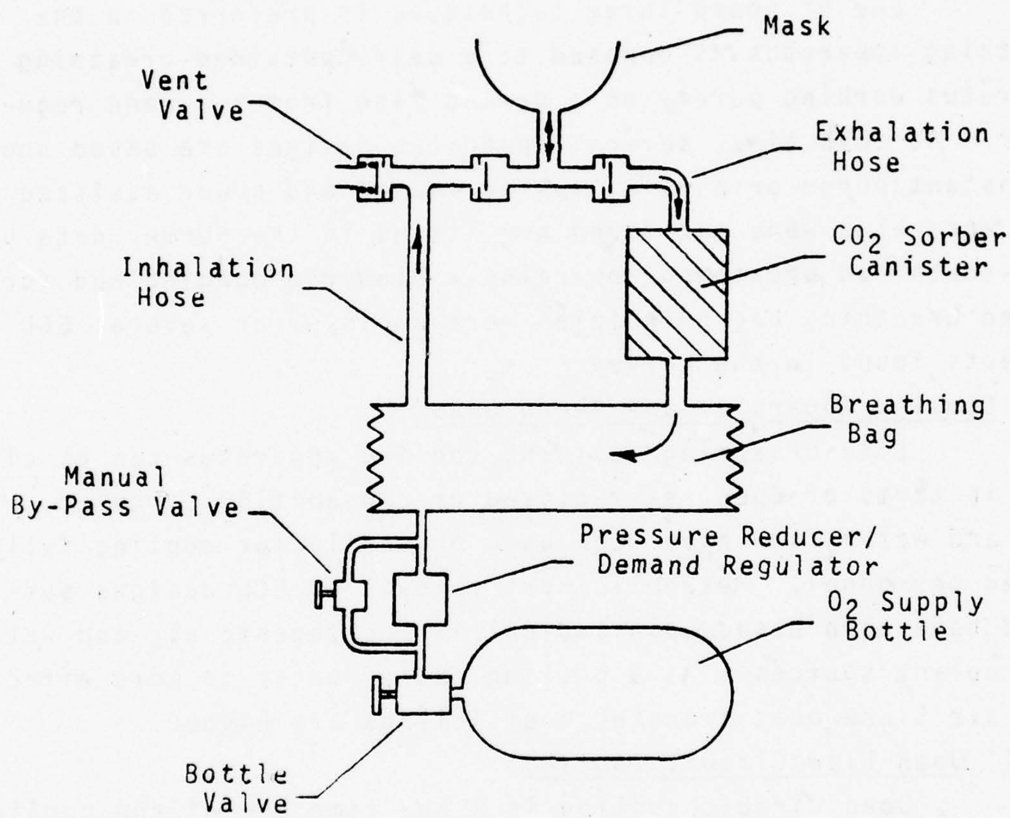

FIGURE 3. CLOSED FLOW CIRCUIT SCHEMATIC
SELF-CONTAINED BREATHING APPARATUS

In addition to a good facepiece seal, maintenance of a positive pressure (0.5-1.0 inch water) will further assure personnel protection. Means by which positive pressure maintenance can be provided to lessen infiltration are:

1. Use of a force loaded breathing bag
2. Provide constant purge
3. Use air blower pressure head

One of these three techniques is preferred in the breathing apparatus as opposed to a self-contained breathing apparatus working purely on a demand flow from a demand regulator. At this time, several apparatus designs are based upon a constant purge principle; spring loaded and power assisted type apparatus were not found nor listed in the survey data on self-contained breathing apparatus. Blowers, purging and force loaded breathing bag principles were employed on several ECU concepts found in the survey.

3.2 Cooling Apparatus and Techniques

Like breathing devices, cooling apparatus can be classified in terms of open, semi-closed or closed flow circuits. Air flow and water flow have been used primarily for cooling fully suited personnel. Metabolic heat removal of ECU designs surveyed have been based upon ambient air, cryogenic air and wet ice for coolant sources. As a cooling media, water is more effective than air since heat transfer coefficients are higher.

3.2.1 Open Flow Circuit Cooling

Open circuit cooling is a one time use of the cooling media. Air is most commonly used because it is ubiquitous. In an open circuit, air is drawn from the ambient surroundings, conditioned accordingly, enters the suit to provide cooling and then passes out of the suit through vents.

3.2.1.1 Vortex Tube

Vortex tubes are small devices weighing about 8 oz. An umbilical is used to supply pressurized air to the vortex tube. At one end of the vortex tube hot air is expelled and

from the other end cool air, which is directed into the suit and subsequently vented. Thus, both cooling and breathing air can be supplied from a vortex tube. This is the most simplistic method of providing both. However, it is not a self-contained unit in that an umbilical connection to a remotely located compressor is required.

It is not practical to have a self-contained vortex tube system as an ECU because of weight and size for compressors required. Vortex tubes operate at a flow rate of 25 cfm and pressure of 60-140 psig. A compressor operating at 60 psig delivering 25 standard cfm air requires a theoretical 3.3 HP. Because of efficiency loss ($\sim$40% efficiency) the actual compressor HP required is about 8.3 HP (21,1500 BTU).

A valve on the vortex tube manipulates the flow split of cold and hot air. For 70% cold air fraction, 30% hot air fraction, approximately 18 cfm cool air is delivered to the suit. Performance data indicates a 1100 BTU/hr cooling rate. This is at the expenditure of 8.3 HP or 21,159 BTU/hr input or an overall efficiency of about 5.2% (1100/21150 x 100 = 5.2%). Although it is impractical for the vortex tube to be a self-contained unit, it becomes practical for use with an umbilical and the availability of a remote compressed air supply.

The vortex tubes are usually attached to the back of the suit. Figure 4 shows the flow schematic of a vortex tube open flow circuit cooling arrangement.

3.2.1.2 Ambient Air Blower

Blowers are used to move ambient air for cooling. A composite layer cooling undergarment, such as used in POTMC, more efficiently cools than do tube distribution types. This is because air flow is contained closer to the skin area, promoting better heat exchange. A composite layer cooling undergarment also gives some protection from exposure to percutaneous contaminants since the air flow would tend to wash out contaminants

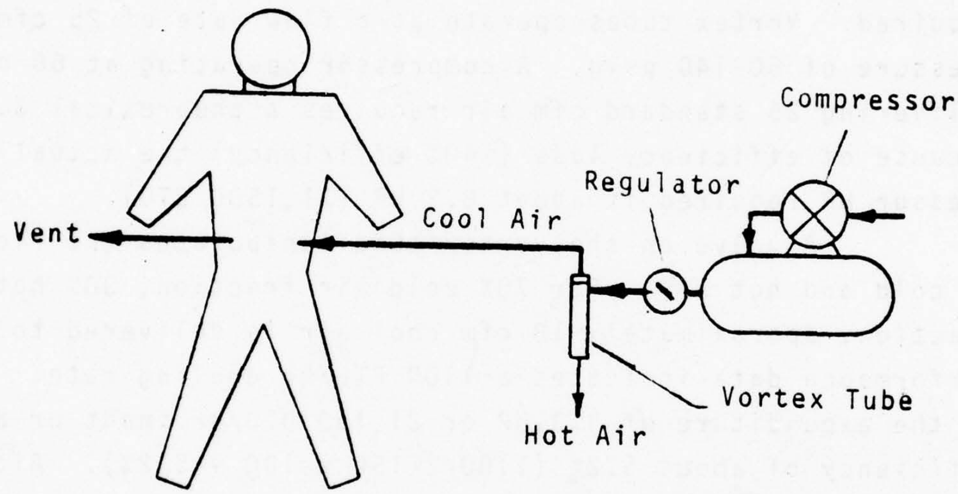

FIGURE 4. VORTEX TUBE OPEN FLOW
CIRCUIT COOLING SCHEMATIC

entering through the suit. A flow of 18 cfm through the POTMC composite layer undergarment results in a pressure drop of 2 1/2 in. water. The blower operates at 12 volts DC at 2 1/2 amps. For a two hour duration, 70 watt-hr battery supply is required. For Ni-Cd batteries, this represents about a five pound battery weight.

Effectiveness of ambient air cooling depends upon prevailing temperature and humidity. Enthalpy of air varies considerably with temperature and humidity.

Temp. (°F)	Rel. Hum. (%)	Enthalpy (BTU/lb)
70	50	16.6
70	60	18.2
70	75	20.5
85	50	25.2
85	75	31.6

The loss in heat removal capacity from 18 cfm air flow (81 lb/hr) between 70F, 50% relative humidity and 85F, 50% relative humidity is 8.6 BTU/lb (25.2-16.6 = 8.6 BTU/lb). At a flow rate of 18 cfm (81 lb/hr), this amounts to 696 BTU/hr variation. When considering an average metabolic heat production rate of 1000 BTU/hr, it can be expected that ambient condition variations change cooling effectiveness.

Ambient air, if used for breathing, must be conditioned by filtering to remove contaminants. For cooling, some maintenance of inlet air temperature and humidity is desirable to more effectively cool, considering various temperature-humidity conditions that will be experienced. This could be moderated by a heat exchanger with wet ice as a refrigerant. Selecting 70F, 50% relative humidity as a condition to maintain for inlet air, eight lb of ice would suffice for ambient air drawn in at 85F, 50% relative humidity; the enthalpy difference and flow rate between these two conditions requires a heat removal rate of 696 BTU/hr ($q = [25.2-16.6]81 = 696$ BTU/hr). For two hours this amounts to 1392 BTU. Heat capacity of 8 pounds of ice is

1456 BTU ($q = 8x144+8[1][70-32] = 1456$ BTU(heat fusion ice = 144 BTU/lb, specific heat water = 1 BTU/lb°F). Allowing five pounds for a battery, one half pound for a blower, eight pounds for water and one and one half pounds for a heat exchanger, a conditioning unit of this type would weigh about 15 pounds.

Figure 5 shows a flow schematic for an open flow circuit cooling system with ambient air conditioning with the wet ice heat exchanger.

3.2.2 Semi-Closed Flow Circuit Cooling

A semi-closed flow circuit cooling device is represented by liquid air type ECU's. Liquid air is stored in a vacuum dewar. It is boiled off and continuously purged through the suit to remove heat and then vented out of the suit. As the liquid is boiled off, it is lost to the atmosphere and is not recoverable.

3.2.2.1 Cryogenic Air

Cryogenic supply such as liquid air used in some ECU designs represents a semi-closed flow circuit cooling device. Liquid air evaporates and heat of vaporization is used to remove metabolic heat. The gaseous air is thereby used for cooling and breathing as it passes into the suit from the ECU. This cooling technique is obtained by continuous purging and constitutes a semi-closed flow circuit. Figure 6 is a schematic of this type device.

A fresh supply of cryogenic air is required with each use period. The cryogenic air charge is about 8-9 pounds, and it is stored in a vacuum dewar. Cryogenic air supply is logistically difficult to support and, therefore, this type of semi-closed flow circuit cooling device employing liquid air is not desirable.

3.2.2.2 Refrigerants, Freon, Ammonia, etc

Other examples of semi-closed flow circuit cooling would be represented by common refrigerants such as freon, ammonia,

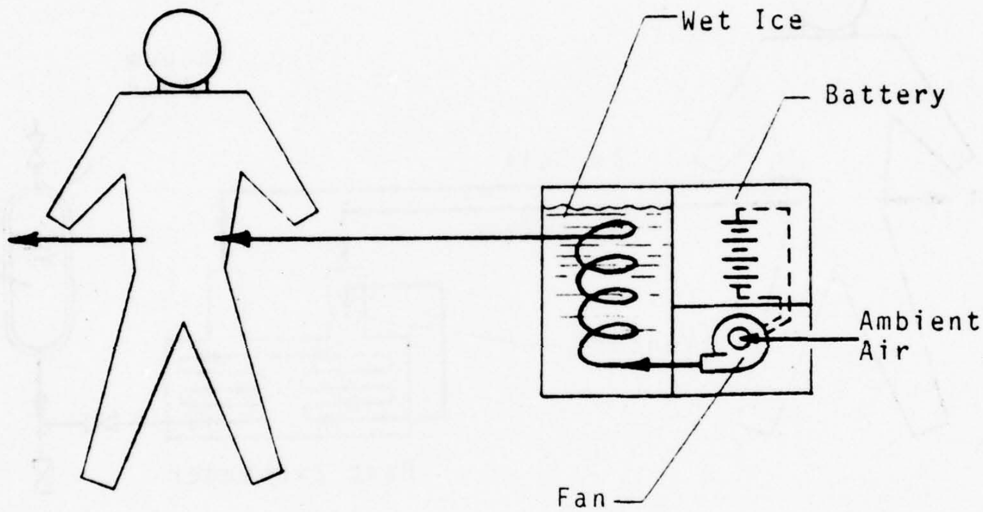

FIGURE 5. AMBIENT AIR OPEN FLOW
CIRCUIT COOLING SCHEMATIC

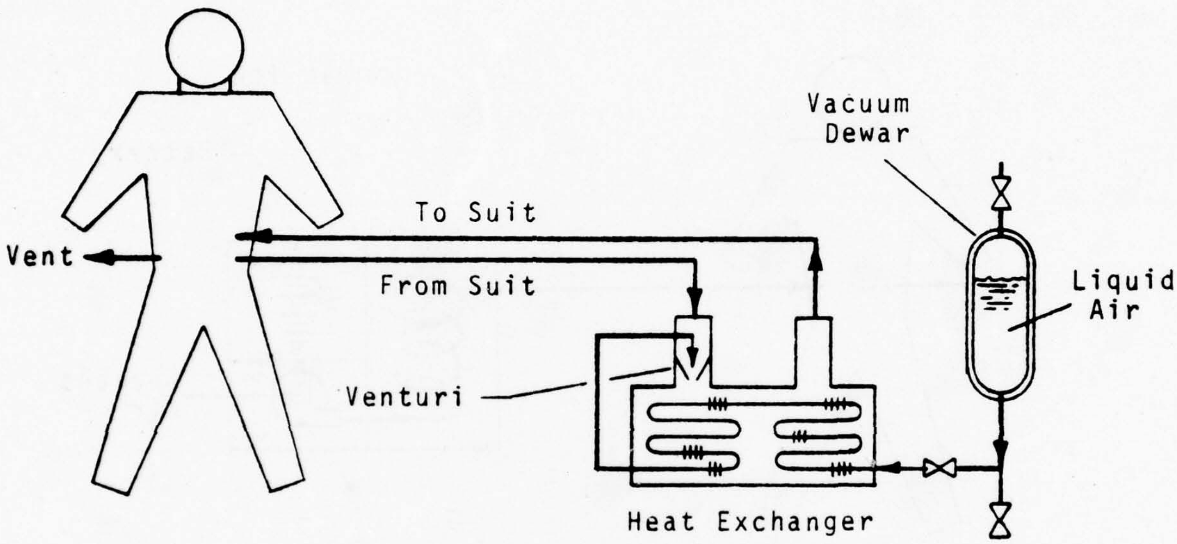

FIGURE 6. CRYOGENIC AIR SEMI-CLOSED
FLOW CIRCUIT COOLING SCHEMATIC

etc., or by water if vacuum were available to effect vaporization. A secondary loop of breathing air would be required with the common refrigerants (freon, ammonia, etc) since they could not be used directly, like air, for both breathing and cooling. Certain refrigerants are undesirable because of ecological considerations and in the case of ammonia, its explosive nature.

To effect water vaporization, an equivalent pressure of 100,000 ft altitude is required. A vacuum pump required to vaporize water would be large, precluding such a system to be self-contained, i.e., capable for personnel to carry with them.

A compressed CO_2 bottle might also be considered, but again the weight of CO_2 and its storage bottle would be prohibitive. For 1000 BTU cooling, $\sim$10 lb CO_2 is required (heat of vaporization is 102 BTU/lb). A size 3 cylinder containing 8 lb CO_2 weighs 30 lb (total weight 38 lb charged).

3.2.3 <u>Closed Flow Circuit Cooling</u>

A closed flow circuit cooling device is one in which a coolant sink, such as ice water, is available, with a secondary water coolant loop recirculating to the heat source, picking up heat and then yielding it to the ice water cooling sink. The ice water coolant sink is contained in a tank with a heat exchanger outside. After the ice water cooling capacity is lost, it can then be placed in a refrigerator to refreeze and be used again. This is a regnerative method, albiet in a batch type manner. Refrigeration units, likewise, maintain their working fluid in storage and are regenerative cooling but continuous in application.

3.2.3.1 <u>Ice Water Pack</u>

A "Cool Head" (mfd. by Acurex-Aerotherm Div.) is commercially available and is a closed flow circuit type of cooling device. These are self-contained units weighing about nine pounds and are about 8 in. x 10 in. x 3 in. in size. A closed flow circuit schematic is shown in Figure 7.

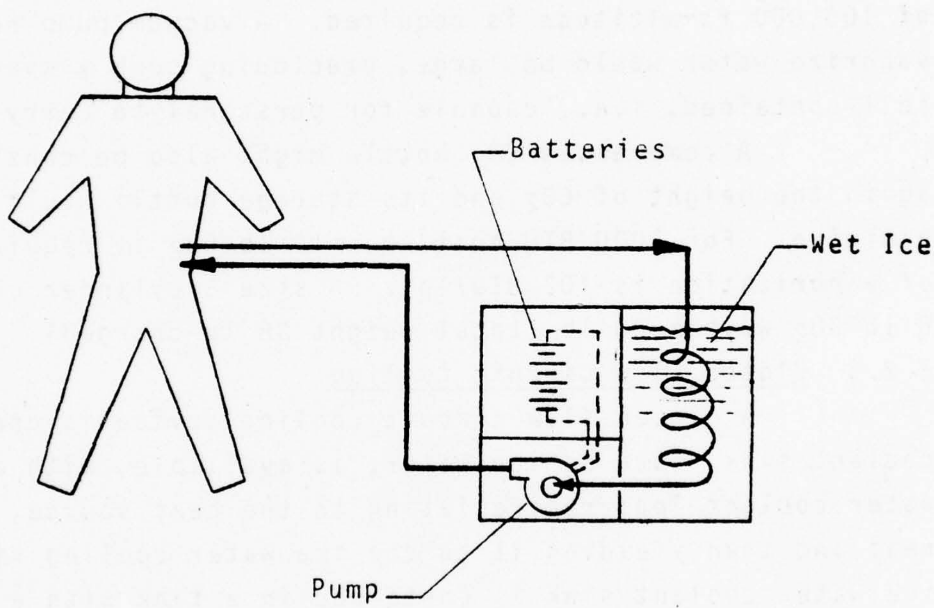

FIGURE 7. ICE PACK CLOSED FLOW CIRCUIT COOLING SCHEMATIC

The packs contain an ice canister, contact heat exchanger, pump, accumulator, and battery. Cooling capacity is 300-400 BTU. About 1/2 gpm water is circulated through the heat exchanger to cool the water and then into a vest and head liner garment. Quick disconnects are used to join the pack with the water cooled vest and head liner inside the suit. The pack is worn on a belt.

Water cooled garments are more effective than air cooled garments. Vest and head liners are made of flexitherm material. These are 4-8 times more effective than liquid cooled suits worn by Apollo astronauts and 10-20 times more effective than air cooled garments.

The ice canister and closed loop flow circuit vest and head liner is a regnerative system. The ice canister is placed in a refrigerator to refreeze the water for reuse. The circulating water stream in the vest and head liner contains ethylene glycol antifreeze to maintain it in a liquid state if the entire pack is placed in the refrigerator.

3.2.3.2 <u>Cooling Vest</u>

Vests have been developed (at Lyndon B. Johnson Space Center) which are slung over the back of the neck and hung over the chest. They are configured somewhat like a flotation collar and are filled with chilled water which does not circulate. The vest is made of heat sealable urethane material put together in sections using flat pattern construction techniques. Simple construction techniques and durable materials make these vests relatively inexpensive to manufacture; its ease of use and effectiveness suggests that it could be used for many applications.

3.2.3.3 <u>Refrigeration</u>

A closed flow circuit cooling system might also be considered with minimized refrigeration units. Refrigeration cycles can be classified as follows:

1. Gas compression
2. Vapor compression
3. Absorption

Some characteristics of some common refrigerations are given in Table 4.

Gas Compression - Refrigeration deals with transfer of heat from a low temperature level to a high temperature. In the case of a gas (air, O_2) compression cycle, power is introduced into the system by compressing a gas or vapor from a low suction pressure to a high discharge pressure. A liquifiable refrigerant which is employed in a vapor compression cycle changes phase from liquid to vapor as it absorbs heat in an evaporator. A gas compression "cold air" refrigeration cycle differs in that the gaseous refrigerant picks up and releases heat without changing phase.

When a Carnot heat engine cycle is reversed, it becomes in effect a "heat pump" or refrigeration cycle. The use of gas (air) as the working fluid produces extreme temperatures and volumes thus requiring very large machines per unit refrigeration capacity. Consequently, a closed cycle gas compression refrigeration system is not feasible as a self-contained unit. Figure 8 illustrates a gas compression closed cycle flow circuit refrigeration schematic.

Vapor Compression - Vapor compression employs a phase change, liquid and vapor, which is primarily used in most commercial equipment. A vapor cycle cooling system consists mainly of components whose function is to cool some fluid outside the system by heat exchange with a primary fluid which is the refrigerant. A compressor withdraws the vapor generated in the evaporator at a low pressure, raises its pressure and discharges the vapor to the condensor. The refrigerant then changes phase from a vapor to a liquid in the condensor thereby discarding heat to a sink. The high pressure liquid refrigerant is expanded

TABLE 4 - CHARACTERISTICS OF COMMON REFRIGERANTS

Refrigerant	Freezing Point °F @ 14.7 psia	Latent Heat of Vaporization (Btu/lb @ 30°F)	Critical Point Temp. (°F)	Critical Point Press. (psia)	*Weight/2 Hrs (lbs) for Open Cycle -Cooling System
Freons:					
R-11	-168	81.37	388.4	635	49.2
R-12	-247	65.36	233.6	596.9	61.2
R-13	-296	39.47	83.9	561	101.4
R-14	-312	58.43 @ B.P.	-49.9	542	68.6
R-21	-211	106.37	353.3	750	37.6
R-22	-256	89.34	204.8	716	44.8
R-113	- 31	69.12	417.4	495	58.0
R-114	-137	59.76	294.3	474	67.0
Ammonia	-107.9	545.0	271.2	1651	7.36
Carbon Dioxide	-109.0	102.2	87.8	1072.1	39.2
Sulfur Dioxide	- 98.0	162.4	314.8	1141.5	24.6
Ethane	-278.0	132.5	90.1	700	30.2
Isobutane	-229.0	153.5	272.7	557.1	26.0
Methyl Chloride	-153.0	174.66	289.6	969.2	23.0
Water	32	1074.0	706.1	3226	3.72
Oxygen (liquid)	-297.4 (B.P.)	91.6	-182	736	43.6
Nitrogen (liquid)	-320.4 (B.P.)	85.9	-233	492	46.6
Methylene Chloride	-142.0	156.7	421	640	25.6
Ethylene	-272.0	84.0	48.8	731.8	47.6
Propane	-310	163.4	202	661.5	24.5
Propylene	-301	123.0	196.5	667.2	32.5
Nitrous Oxide	-152	109.8	96.5	1050.0	36.5
Methane	-297	202.0 @ B.P.	-115.8	673.0	19.8
Methyl Formate	-147.5	233.5	418	607	17.1
Ethylamine	-115	278.4 @ 5°F	362	815	14.4
Methylamine	-134	369.5 @ 5°F	314	1082	10.8
n-Butane	-211	120.0	306	550	33.3
Carrene 7	-247		221	631	
Air	-351	115.0 @ B.P.	547	-	34.8

* Based on Cooling Load of 2000 Btu/hr

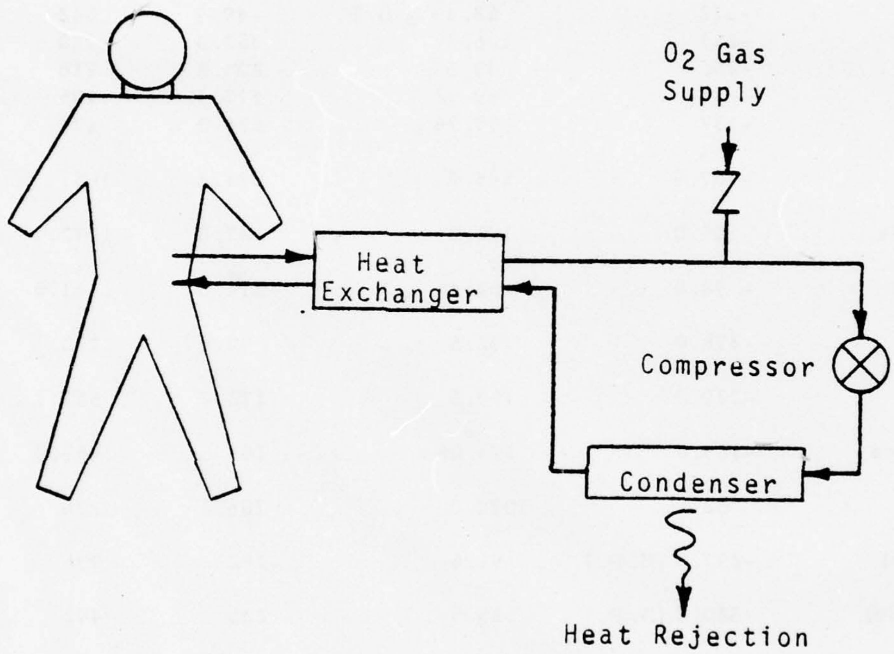

FIGURE 8. GAS COMPRESSION-CLOSED LOOP FLOW
CIRCUIT REFRIGERATION SCHEMATIC

and fed to the evaporator to complete the cycle. Like the gas compression cycle, the vapor cycle would be large and not feasible as a self-contained unit. Figure 9 shows a vapor compression closed flow circuit refrigeration schematic.

Absorption - Absorption refrigeration systems operate differently than the gas and vapor compression systems in that heat is used directly as the operating energy instead of the energy input being in the form of mechanical work of compressors. If the compressors in a vapor compression system (See Figure 9) were replaced with a generator-absorber assembly, a basic absorption system cycle would result as shown in Figure 10.

Ammonia-water and water-lithium bromide are the most important absorption systems in use. The generator-absorber assembly pumps refrigerant vapor from the evaporator to the condensor by first absorbing the vapor in a liquid, building up the pressure of the liquid to that at the condensor, and then liberating the vapor by heating the solution in the generator. A pump is used to draw strong solution (rich in refrigerant) to the generator while the weak solution (after the vapor has been driven off) is returned to the absorber by a valve operating under the existing pressure differential of the high and low sides of the system. The addition of heat in the generator raises the temperature of the solution, distilling off refrigerant vapor at high pressure and temperature. From the generator, the high temperature, high pressure vapor proceeds to the condensor radiator, expansion valve and evaporator, as it does in the vapor compression system.

The complexity and weight of the absorption refrigeration system is such that it is not feasible as a self-contained unit.

These refrigerant type systems are presented as background information for ECU cooling techniques. Weight, bulk and power requirements for these units would be prohibitively large for a self-contained design; estimated weights of 70-90 lbs and power of 300-800 watts would be required.

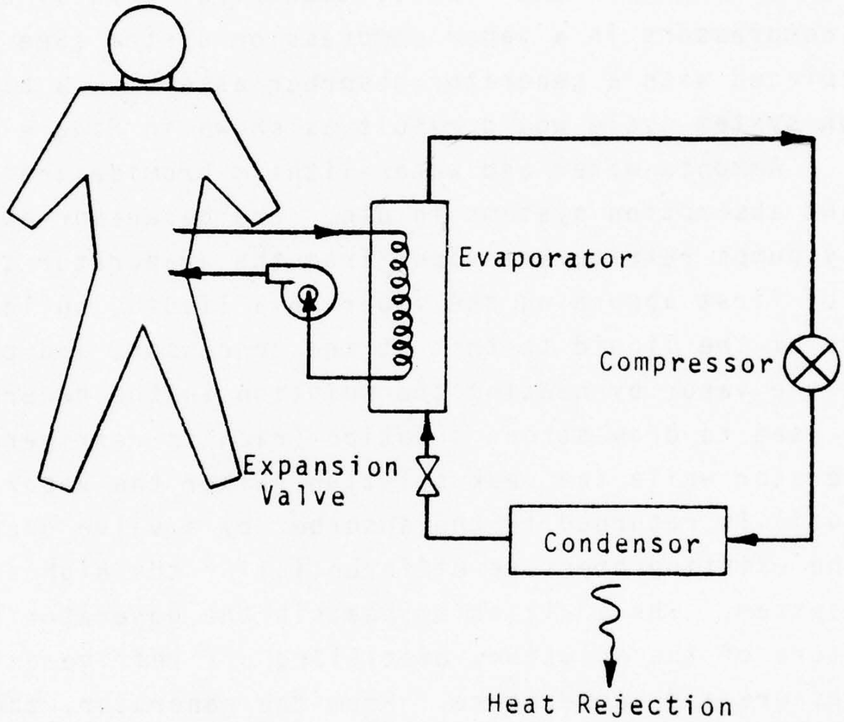

FIGURE 9. VAPOR COMPRESSION-CLOSED LOOP FLOW CIRCUIT REFRIGERATION SCHEMATIC

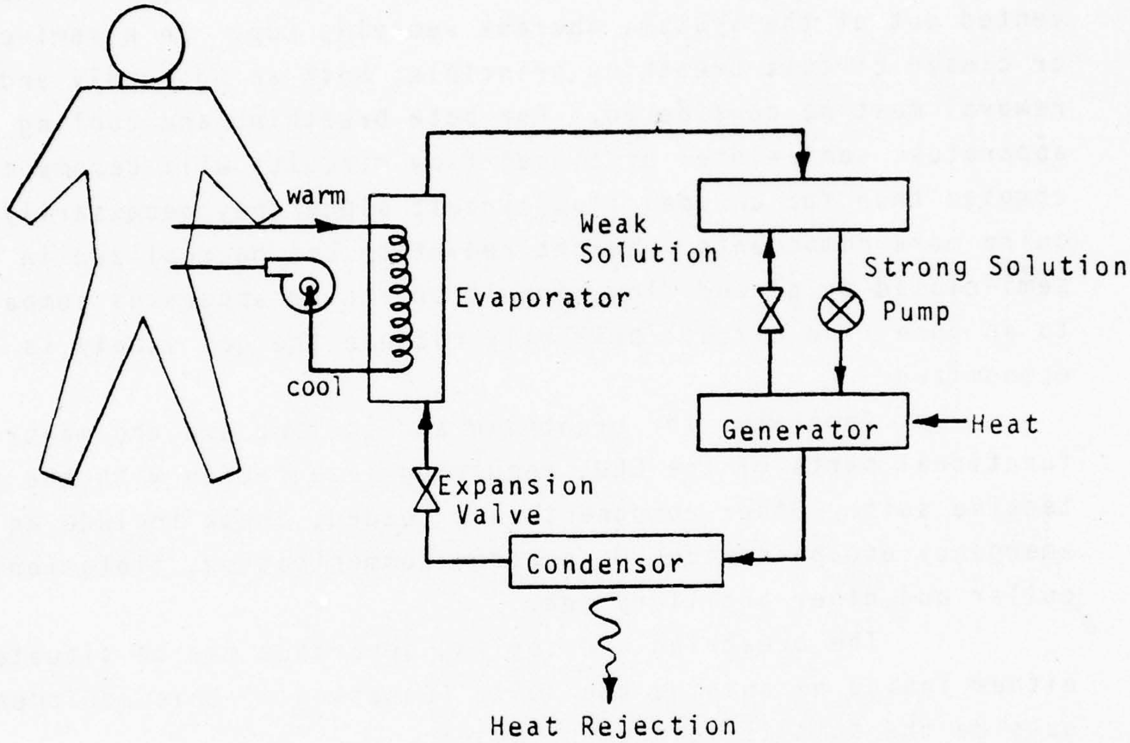

FIGURE 10. ABSORPTION CLOSED LOOP FLOW
CIRCUIT REFRIGERATION SCHEMATIC

4.0 CONCEPTUAL DESIGN ANALYSIS

Breathing and cooling circuits have been discussed in general terms in the previous section. Selection of concepts and facets of each choice requires individual evaluation to determine feasibility.

If an open cycle breathing apparatus is considered, only O_2 must be supplied since exhalation gases are continuously vented out of the system, thereby removing CO_2. In a semi-closed or closed circuit breathing principle, both an O_2 supply and CO_2 removal must be considered. For both breathing and cooling apparatus, semi-closed or closed flow circuits will become more complex than for an open flow circuit since they necessarily require more components. Weight reduction can be realized in a semi-closed or closed flow circuit breathing apparatus compared to an open flow circuit primarily because the gas supply is economized.

Apparatus for breathing and cooling are the major functional parts of the ECU, requiring integration with the protective suit. Other components are needed; these include an emergency escape device, O_2 sensor, communication, flotation collar and other ancillary gear.

The breathing and cooling apparatus may be situated either inside or outside the suit. Location of this equipment outside the suit is favored because:

1. Personnel will have more command of their equipment and be able to don and doff apparatus more quickly.
2. Provides accessibility for better operational ease.
3. Permits more mobility and would improve work task effectiveness.
4. Be more comfortable and less constraining than if it were inside the suit.

Four types of ECU concepts are presented in paragraph 2.4 These are all based upon modular arrangement. Modularizing

and field refurbishing are suggested as an approach to reduce weight, yet permit extending service time.

4.1 ECU-1 Concept Analysis

This concept is based upon a separate breathing air supply and cooling supply modules. Breathing air would be supplied only to the head (helmet) region isolated from the body (suit) by a neck seal.

A full facepiece or half mask appears to be required although not having either is preferable. Calculations indicate that a mask is required. The measured free volume in the POTMC helmet is 0.69 cu ft (19.5 liters). The actual free volume when in use is less; the head volume and other parts in the helmet will reduce free volume. Assume the free volume to be 0.25 cu ft, O_2 consumption at a rate of 3 cu ft/hr with CO_2 production (respiratory quotient, RQ = CO_2/O_2 ratio of 0.82) of 2.46 cu ft/hr.

Typical air compositions are:

	Inspired Air Comp. (%)	Expired Air Comp. (%)
O_2	21	13
CO_2	0.04	5.27
N_2	78.5	75.2
H_2O	0.53	6.2

The lung tidal volume flow rate (also the flow rate in the circuit) is about 0.783 cu ft/min.

$$\text{flow rate} = \frac{2.46 \text{ cu ft x hr}}{\text{hrx60 min } (0.0527-.0004)} = 0.783 \text{ cu ft/min}$$

Let x = volume of CO_2, cu ft
t = time, minutes

The rate equation representing CO_2 concentration change in the helmet is:

change in CO_2 volume = rate in - rate out

$$dx = \frac{2.46}{60}\,dt - \frac{x(0.783)}{0.25}\,dt$$

$$dx = 0.041dt - \frac{x}{0.319}\,dt$$

$$dx = (0.0131 - x)\frac{dt}{0.319}$$

$$\frac{dx}{(0.0131 - x)} = \frac{dt}{0.319}$$

Integrating

$$\ln(0.0131 - x) = 3.135t + c$$

or

$$x = 0.0131\left(1 - \frac{1}{e^{3.135t}}\right)$$

Percent CO_2 concentration in helmet is $\frac{x}{0.25} \times 100$. Volume and percent CO_2 in the helmet is:

Time (min)	Vol. CO_2 (x) (cu ft)	% CO_2
1/4	0.0071	2.84
1/2	0.0104	4.15
1	0.0125	5.01
2	0.0131	5.23

Prohibitively high CO_2 concentration results at this flow rate because of the large dead space volume in the helmet; and, therefore, a facepiece is required.

In POTMC, 6 cfm is circulated through the helmet. This circulation rate satisfactorily maintains safe CO_2 concentrations.

Change in CO_2 vol. = rate in - rate out

$$dx = \frac{2.46}{60}\,dt - \frac{x(6)}{0.25}\,dt$$

$$dx = 0.041dt - 24xdt$$

$$\frac{dx}{(0.00171 - x)} = 24\,dt$$

$$\ln(0.00171 - x) = 24t + c$$

$$x = 0.00171 \left(1 - \frac{1}{e^{24t}}\right)$$

Volume of CO_2 and percent CO_2 in helmet is:

Time (min)	x Vol. CO_2 (cu ft)	% CO_2
1/8	0.00162	0.65
1/4	0.001705	0.68
1/2	0.00171	0.684

In the POTMC helmet where 6 cfm air flow is maintained, CO_2 concentration is about 3/4% and there is no need for a mask as in the case of a low flow rate rebreather apparatus.

4.1.1 Rebreather Module

The components are an O_2 bottle, shut off valve, pressure reducer, demand regulator, CO_2 scrubber canister, breathing bag, inhalation-exhalation hoses and check valves, mask, overpressure and purge valve, protective cover, harnesses, etc. See Figure 11.

4.1.1.1 O_2 Supply

A requirement of 5.4 cu ft O_2 for two hour service time is given in Table 1 based upon metabolic heat production of 1000 BTU/hr and allowance for 55% excess (1.75 cu ft O_2/hr x 2 hr x 1.55 = 5.4 cu ft O_2). A steel bottle, 3 11/16 in. dia x 11 3/8 in. long weighing approximately 4 lb can store 6.8 cu ft O_2 at 2200 psig to meet O_2 supply requirements.

4.1.1.2 O_2 Bottle On-Off Valve

An on-off valve is screwed into the bottle. This valve would be equipped with ports to attach pressure gage, a fill port and an outlet port for connection to a pressure reducer. A rupture disc is provided on the valve to protect against bottle overpressure. Weight of 1/2 in. NPT bottle valve with pressure gage and fill port is about one pound.

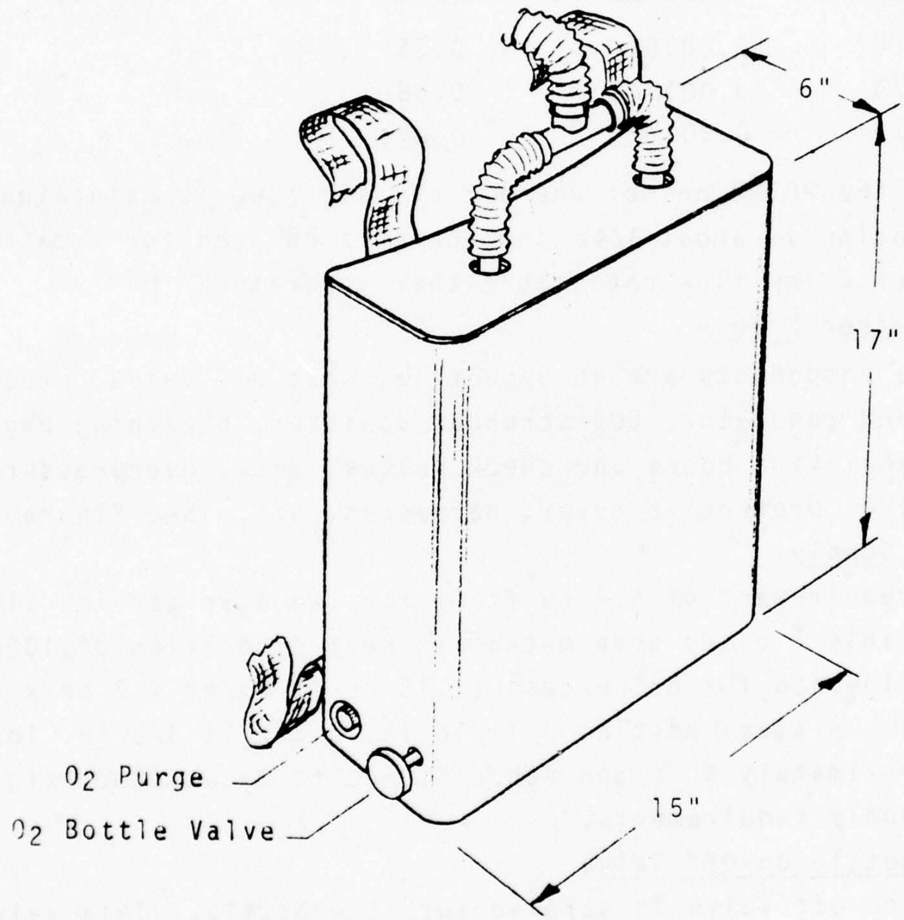

FIGURE 11. REBREATHER MODULE

4.1.1.3 Pressure Reducer

As O_2 is removed from the bottle, pressure decreases. A constant supply pressure is maintained by the pressure reducer (regulator) which is set at a nominal 70 psig delivery pressure. The weight of a pressure reducing regulator is about one pound.

4.1.1.4 Demand Regulator

The pressure reducing valve supplies a constant 70 psig pressure to the upstream end of the demand regulator. The demand regulator opens upon sensing any negative pressure in the circuit and feeds O_2 into the system. The weight of a demand regulator is about 0.7 pounds.

4.1.1.5 Breathing Bag

The breathing bag serves as an accumulator for gas in the circuit. Volume of the breathing bag should be at least five liters, in excess of lung tidal volumes ranges of one and half to two liters. The breathing bag is made of flexible material such as neoprene rubber. Weight of a breathing bag is about two pounds. The breathing bag is located downstream of the CO_2 scrubber canister and to some extent serves as a heat exchanger to dissipate some of the heat produced by the CO_2 sorbtion canister. O_2 from the demand regulator(or a constant flow device) is fed into the breathing bag. Gas from the breathing bag is fed to the inhalation tube connected to the mask via a check valve manifold assembly.

4.1.1.6 Inhalation-Exhalation Hoses

Inhalation-exhalation hoses connect to a check valve manifold assembly joined to the mask. The inhalation hose comes off the breathing bag; the exhalation hose connects to the CO_2 sorption canister. Typical weight of the two breathing hoses is about 0.55 pounds.

4.1.1.7 Check Valve Manifold Assembly

Check valves direct flow into the mask. An inhalation check valve opens upon inhalation, closing off the exhalation valve, thereby admitting fresh regenerated breathing supply to the

mask. Upon exhalation, the reverse occurs, the inhalation check valve closes and the used expired air passes through the exhalation valve into the exhalation hose and on to the CO_2 sorption canister.

4.1.1.8 <u>CO_2 Sorption Canister</u>

The requirement for the CO_2 sorption canister is to remove 4.5 cu ft CO_2 (0.55 lb). Materials used to remove CO_2 are lithium hydroxide, soda lime, baralyme, etc. Lithium hydroxide is the most efficient on a weight basis but is also the most expensive. CO_2 sorption canisters must be designed to prevent any of the caustic dust present in the CO_2 sorbers from entering the flow circuit because it is irritating to mucous membranes. Filters are used on each end of the canister to prevent caustic dust escape.

Theoretical and actual CO_2 sorption removal of these materials is as follows:

CO_2 Sorber Chemicals	lbs Material/lb CO_2 Theoretical	Actual	lbs Material Required for 0.55 lb CO_2
Lithium Hydroxide	1.10	1.50	0.83
Soda Lime[1]	2.05	4.10	2.26
Baralyme[2]	2.20	5.50	3.03

[1]Soda lime composition: 4.5 wt % NaOH, 17.5 wt % H_2O, 78 wt % $Ca(OH)_2$

[2]Baralyme composition: 80 wt % $Ca(OH)_2$, 20 wt % $Ba(OH)_2 \cdot 8H_2O$

The CO_2 sorber chemicals are granular materials and are packaged in canisters. Considering baralyme as the material because of its low cost and availability, three pounds are required. Allowing 1 1/2 lb for the canister and filters, the weight of the CO_2 sorber canister assembly is approximately 4 1/2 pounds.

Three pounds baralyme represents a volume of 90 cu in. For a 5 in. diameter canister, the baralyme bed length would be about 4 3/4 in. long. Breathing rate is sinusoidal, maximum instantaneous rates reach 150 liters/min. Using this rate, the pressure drop across the baralyme bed would be 0.5 in. water.

4.1.1.9 Protective Case, Harnesses

The rebreather assembly is best contained in a plastic case to reduce exposure to contamination. ABS plastic (ρ = 64 lb/cu ft) case (17 in. x 15 in. x 6 in. x 3/32 in. tk. material) would weigh about two pounds. Weight of harnesses and other support brackets would add another two pounds.

4.1.1.10 Rebreather Weight Estimate

Estimated weights of two hour closed flow circuit rebreather components are as follows:

Component	
O_2 bottle	4.00
O_2 gas (6.8 cu ft)	0.61
O_2 bottle on-off valve	1.00
Pressure reducer	1.00
Demand regulator	0.63
Breathing bag	2.06
Hoses	0.55
Check valve manifold	0.25
Mask	1.00
CO_2 sorber canister	4.50
Protective case	2.00
Harnesses, supports	2.00
Miscellaneous, alarms, etc.	1.40
Total	21.00 lbs

The estimated weight for a two hour rebreather, closed flow type circuit is 21 lbs. A 45 minute apparatus with semi-closed flow circuit, in which a steady 3.6 lpm flow is available, has a weight of 17 lbs. Comparatively, the closed circuit arrangement economizes on O_2 usage and permits longer operation with a slight increase in weight.

4.1.2 Cooling Module

In a cooling system, the metabolic heat rate requirements and transient variations are different than those in a breathing apparatus. The breathing apparatus must have more than enough capacity to handle the immediate demand, following variations in gas flow requirements. Immediate response of the breathing apparatus gas supply is required since instantaneous demand rates of up to 150 liter/min may occur due to breathing patterns when the nominal usage rate is of the order of 1-2 liter/min. A cooling system therefore need not have sufficient rate capacity to handle all metabolic heat requirements. Requirements of concern are to have sufficient heat transfer capacity to handle the average heat load and to have a heat sink capacity greater than the total integrated heat load for the mission.

The integrated heat load requirement for the ECU was estimated to be 2400 BTU for a 2 hr period, the average rate being 1200 BTU/hr. The 1200 BTU/hr is divided between the metabolic heat rate production(1000 BTU/hr) and equipment heat production input (200 BTU/hr). The equation relating metabolic heat production with O_2 consumption is:

$$Q = 5.0\ V_{O_2}$$

$$Q = \text{Kcal/min}$$

$$V_{O_2} = \text{liters/min } O_2$$

$$Q = 5.0 \times \frac{1.75\ ft^3\ O_2}{hr}\ \frac{28.3\ liters}{ft^3} \times \frac{Kcal}{0.252}\ \frac{BTU}{Kcal} = 983\ BTU/hr$$

The thermoregulatory system proposed for ECU-1 concept is a water cooling module. It would consist of a heat sink and a liquid circulation garment. This system has been developed for use by miners working in 120F ambient mines. Three garment configurations have been evaluated: (1)head cooling only, (2) thoracic cooling only and (3) head and thoracic cooling.

The head cooler would remove 150 BTU/hr regardless of total metabolic rate. The head-thorax garment heat removal was found to vary linearly from 200 BTU/hr at 1.42 cu ft O_2/hr to 500 BTU/hr at 3.56 cu ft O_2/hr (about 250 BTU/hr at 1.75 cu ft O_2 hr). The ratio of garment heat removal is essentially constant at ~25% for the combined head and thorax garment. With the head garment it decreased from 40-50% for sedentary to less than 10% for the higher metabolic rates.

Flexitherm, a flexible heat sealed coated fabric, is used in the garments and has integrally formed liquid circulation channels. This material is also used in a wet ice heat sink as a heat exchanger, incorporating inlet and outlet manifold and multiple closely spaced, parallel flow paths to form a simple, flexible and high thermally effective contact heat exchanger. The heat exchanger patches require 10-15 psig to inflate the flow passage. This is done with a pump circulating water at a rate of 40 lb/hr (0.08 gpm). The pump uses 12 VDC at 0.5 amps (6 watts). An accumulator (180 cc) is used to accommodate volume difference between the operating and idle modes and a pressurization system to maintain the patch back pressure. Although pressure of 10-15 psig is applied by the pump the flow through the heat exchanger is not large and therefore the pressure drop is low. A 1.5 amp-hr battery capacity is used to power the pump. This is an 18 watt-hr capacity, adequate for at least 2 hr operation. A nickel cadmium battery having 18 watt-hr represents about one pound weight. Figure 12 gives battery watt-hr output per pound of battery. Because of the low current flow and voltage, the design is intrinsically safe.

These "Cool Head" packs and garments are available from Acurex-Aerotherm. Weight of the pack is about 9 lbs, the size is approximately 8 in. x 10 in. x 3 in. A one liter tank filled with water can be easily regenerated for cooling by

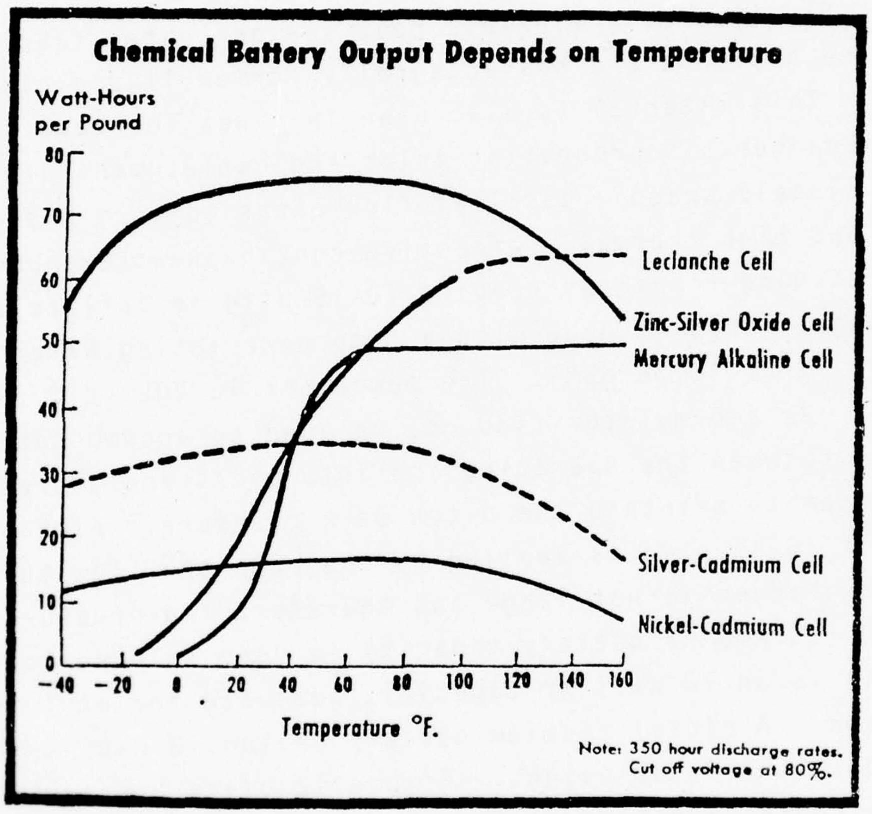

FIGURE 12. BATTERY OUTPUT-WEIGHT RELATIONSHIP

placing it in a refrigerator. Batteries can be recharged between use periods.

The garments are connected to the heat sink with shut-off type quick disconnects on tygon tubes. Alcohol at a concentration of 1-4% is used to minimize volume changes associated with freezing in the steel water cartridge. Antifreeze solution is also used in the circulating loop to prevent freezing. The one liter cartridge can be easily replaced with a fresh refrozen cartridge without disturbing the sealed circulating loop. A by-pass valve is used to adjust water flow to the garment.

The "Cool Head" pack represents a cooling module which is a closed flow circuit system and is regenerable. Although the expected performance of the "Cool Head" module is 250 BTU/hr at a metabolic heat production rate of 1000 BTU/hr (~25%), its effectiveness permits its use without adverse physiological effects.

Figure 13 shows the cooling module. The head/vest garment has been evaluated by calculation.[(3)] This data indicates that at an ambient of 90°F and metabolic rate of 675 BTU/hr, tolerance time is about 2 1/4 hour. The maximum duration was defined to be the time required for thermal storage of 1000 BTU or body weight loss of 5% to be reached. As ambient temperature increases, tolerance time decreases and at 120°F, tolerance time is about a half hour.

For a 983 BTU/hr metabolic rate and ambient 70-90F, tolerance time would be about one hour. Ice canisters are easily replaced to maintain cooling effectiveness. Spent ice canisters are removed and replaced with fresh canisters stored in a container. It is undesirable to use the module to the extent that personnel reach tolerance limits, therefore ice canister replacement will be required for two hour mission durations.

Figure 14 shows a flow schematic of the cooling module. Water circulates from the module to the head liner, flow splits

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(3) A Portable Personal Cooling System for Mine Rescue Operations, ASME Publication, 77-ENAS-53.

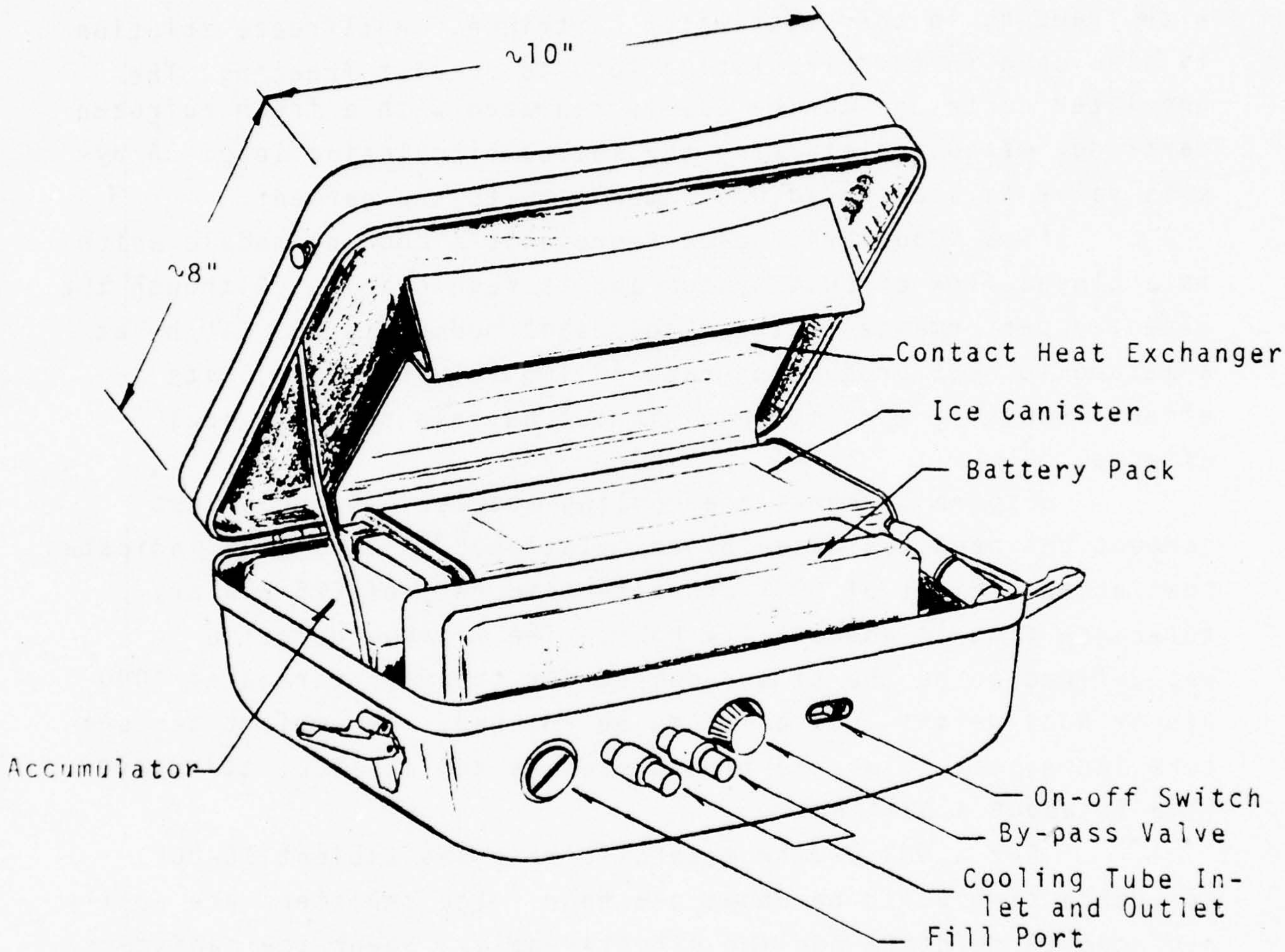

FIGURE 13. COOLING MODULE "COOL HEAD"

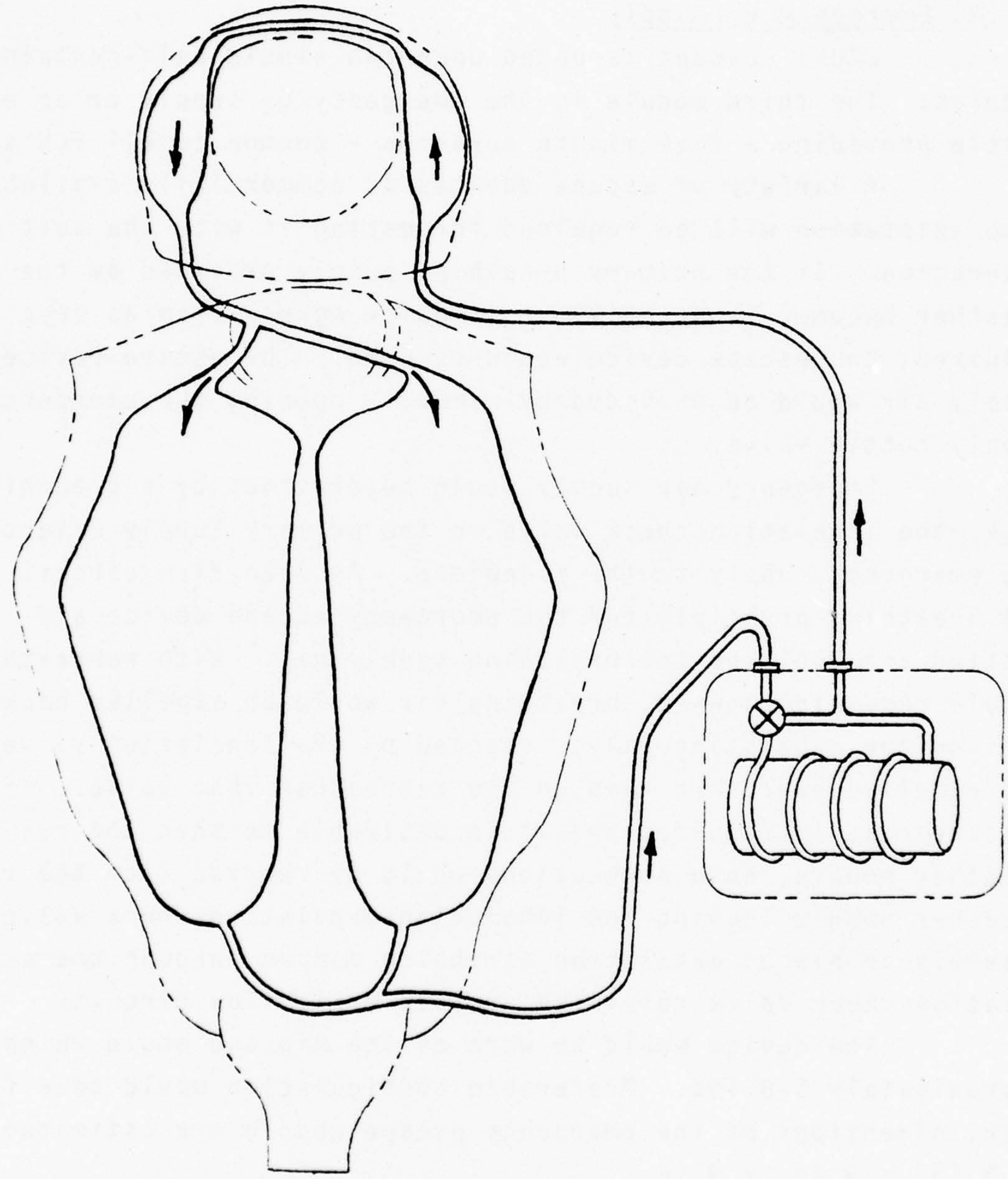

FIGURE 14. COOLING MODULE FLOW SCHEMATIC

through the vest, rejoins and returns to the module to complete the circuit. The weight of the head/vest garment is approximately 2 lb. The weight of the cooler and head/vest garment is a total of 11 lbs.

4.1.3 Emergency O_2 Supply

ECU-1 concept is based upon two single self-contained modules. The third module is the emergency O_2 supply or an egress bottle providing a five minute duration - common to all ECU's.

A variety of escape devices is commercially available. Some adaptation will be required for mating it with the suit configuration. If the primary breathing supply provided by the rebreather becomes inoperative or if quick egress from an area is required, the escape device would be used. The escape device supply air would be provided by manually opening the emergency supply bottle valve.

Emergency air supply would be provided by a breathing hose, the inhalation check valve on the primary supply diverting the emergency supply to the facepiece. An open flow circuit is the breathing principle for the emergency escape device and bottled air would be the breathing supply gas. With rebreather module remaining donned, breathing air would be expelled back through the exhalation valve, checked by the inhalation valve, and expelled overboard through the rebreather vent valve. If quick egress is required and it is desirable to shed the rebreather module, hose connections would be removed from the rebreather module leaving the inhalation-exhalation check valve assembly in place; exhalation air being dumped through the exhalation check valve retaining an open cycle flow circuit.

The device would be worn on the hip and would weigh approximately 5-8 lbs. Preferable configuration would be a flat pack, dimensions of the emergency escape module are estimated to be 3 in. x 8 in. x 9 in.

4.1.4 ECU-1 System Integration

Three components discussed for ECU-1 concept are the rebreather, cooler and emergency escape module. These would require integration with the present POTMC suit accordingly.

The head/vest cooling garment is donned. The flow circuit schematic is shown in Figure 14; water flow is first directed to the head before flowing to the vest. Water is chilled at 55-65F from the cooling module. It has been found (4-6) that the head both requires and comfortably can tolerate lower contact temperatures than other body areas for a given heat removal rate. The head acts as an intermediate heat exchanger before it is circulated to the thorax (upper torso-chest area). Water is at a chilled 55-65°F from the cooling module. A temperature drop exists across the flexitherm garment material. Normal skin temperature is 88F. Nominal skin temperature with the garment is held at about 82F; at about 78F skin temperature, vasoconstriction occurs and is to be avoided. The by-pass value on the cooling module permits comfortable temperature control by personnel who will accordingly adjust for their personal preference. After making necessary communication head gear attachments, the butyl protective suit is next donned with the cooling garment connection made through the suit, in the upper right hand side chest region. The cooling module is belt-worn on the outside of the suit. Tubing from the cooling module is joined to the cooling garment by quick disconnect fittings, completing the cooling circuit hook up.

The emergency escape apparatus would be donned on the outside of the suit. A shoulder strap, belt combination being used to secure it to personnel. The rebreather is donned on the chest, outside the suit, using shoulder and waist harnesses. A quick disconnect from the rebreather manifold joins the rebreather circuit to the helmet using the existing hole in the helmet. An oral nasal mask joined to the helmet is attached to the head with straps.

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(4) Water Cooled Garments, S.A. Nunnely Space Life Sciences, 2:335-360, 1970.

(5) Head Cooling in Work and Heat Stress, S.A. Nunnely, et al. Aerospace Medicine, 42, 1971, pp 64-68.

(6) Effect of a Cooling Hood on Physiological Responses to Work in a Hot Environment, E. Shvarte, Journal of Applied Physiology 29, 1970, pp 36-39.

Since the oral-nasal masks effects a closed loop breathing circuit, it is not necessary to have a neck seal. An alternate arrangement might consider entering the breathing hoses into the suit under the neck seal. Another alternate for consideration is the use of a flexible helmet with ring for attachment to the suit and a hard hat for head protection.

The requirement for the ECU weight set in Task I was 30-35 lbs. Weight estimate for ECU-1 concept is 34-37 lbs.

Component	Est. Weight (lbs)
Rebreather	20
Cooling Module	9
Emergency Escape Module	5-8
	34-37 lbs

Weight of the head/vest garment is about 2 lbs. The POTMC composite layer ventilation undergarment weighs 6.6 lbs and a weight savings of 4.6 lbs is obtained with the liquid cooled garment.

The cooling module would not have enough heat sink capacity for two hours at an average 1000 BTU/hr metabolic heat production rate with a single ice canister. Additional ice canisters would be supplied, installed when they are needed, and maintain the cooling module at the same weight. Weight of the butyl suit (9 3/4 lbs), boots and gloves (6 1/4 lbs) and helmet (3 3/4 lbs) is 19 3/4 lbs. Total system weight, the ECU, suit and helmet, is estimated at 53 3/4-56 3/4 lbs. The weight of the currently used POTMC ensemble using the XM-41 charcoal filter back pack is 70-75 lbs.

Controls would consist of a toxic sensor in the helmet to monitor for any outside contaminant infiltration in the helmet. A diverter valve on the cooling module controls water flow throughout to the head/vest garment. On the rebreather, an audible low pressure alarm is provided to alert when the O_2 supply bottle pressure drops to approximately 25% (500 psi) of its initial

pressurization ($\sim$2000 psi). No gas is wasted with the audible alarm. In addition, a pressure gage gives a visual indication of the supply. An O_2 sensor need not be used; a CO_2 sensor being more applicable to indicate the degree of the CO_2 sorption canister depletion. However, O_2 and CO_2 sensors are not usually part of self-contained breathing devices. The CO_2 sorption canisters are sized commensurately with the O_2 supply since the usage of O_2 is directly related to CO_2 production. Work tests are conducted with the breathing devices during which time gas concentration is monitored as part of the quality control assurance by the manufacturer.

4.2 ECU-2 Concept Analysis

Basic components for ECU-2 concept consist of a rebreather, ice canister cooler and emergency escape modules. These components would be arranged within a single pack. The ECU-2 concept would retain modular arrangement for field refurbishing to extend service time, particularly cooling. ECU-2 would be designed for back mounting and donned outside the protective suit.

As discussed previously in ECU-1 concept, circulation rate from the lungs is not adequate for maintaining safe CO_2 concentration in the helmet. A facepiece is necessary to direct exhaled breath into a CO_2 sorber canister. If a blower were used, circulation rate of 6 cfm would maintain acceptable CO_2 concentration in the helmet and a mask would not be necessary.

A battery powered blower circulating 6 cfm through the breathing apparatus and helmet removes the need for a facepiece and is discussed as a consideration. A blower is a means of maintaining positive system pressure, and also reduces personnel breathing effort. However, the blower and battery pack adds weight and increases system complexity.

4.2.1 Rebreather Module

Parts required for the rebreather include the O_2 supply bottle, bottle valve, pressure reducer demand regulator, breathing bag, hoses, check valve manifold, mask, CO_2 sorber canister, low

pressure alarm, and miscellaneous parts and fittings. Functions of these parts are the same as discussed for ECU-1 concept.

Weight of the rebreather parts, with exception of the protective case and donning harnesses, is estimated to be 17 lbs. Lung power of personnel circulates and regenerates the gas in the breathing apparatus.

Component	Weight (lb)
O_2 Bottle	4.00
O_2 Gas	0.61
O_2 Bottle On-Off Valve	1.00
Pressure Reducer	1.00
Demand Regulator	0.70
Breathing Bag	2.06
Hoses	0.55
Check Valve Manifold	0.25
Mask	1.00
CO_2 Sorber Canister	4.50
Miscellaneous, alarms, fittings, etc.	1.33
	17.00 lb

A blower is reviewed here briefly for weight tradeoff as opposed to the lung powered rebreather circuit discussed above. A breathing mask is not necessary with a blower circulating 6 cfm. The POTMC helmet would require modification for inlet and outlet ports and a neck seal. Breathing pulsation can be reduced by an accumulator, similar to a breathing bag but of smaller volume. Elimination of the mask would reduce weight by about one pound but would be offset by additional weight of a blower and battery pack.

Figure 15 shows the theoretical power required for a blower. About 6 watt-hr power is calculated for 6 cfm at 4 inch water head for a two hour period. Allowing for a 33% efficiency and a 50% extra battery reserve, the battery watt-hrs required is

$$\text{power supply} = \frac{6 \text{ watt-hrs}}{0.33} \times 1.5 = 27 \text{ watt-hrs.}$$

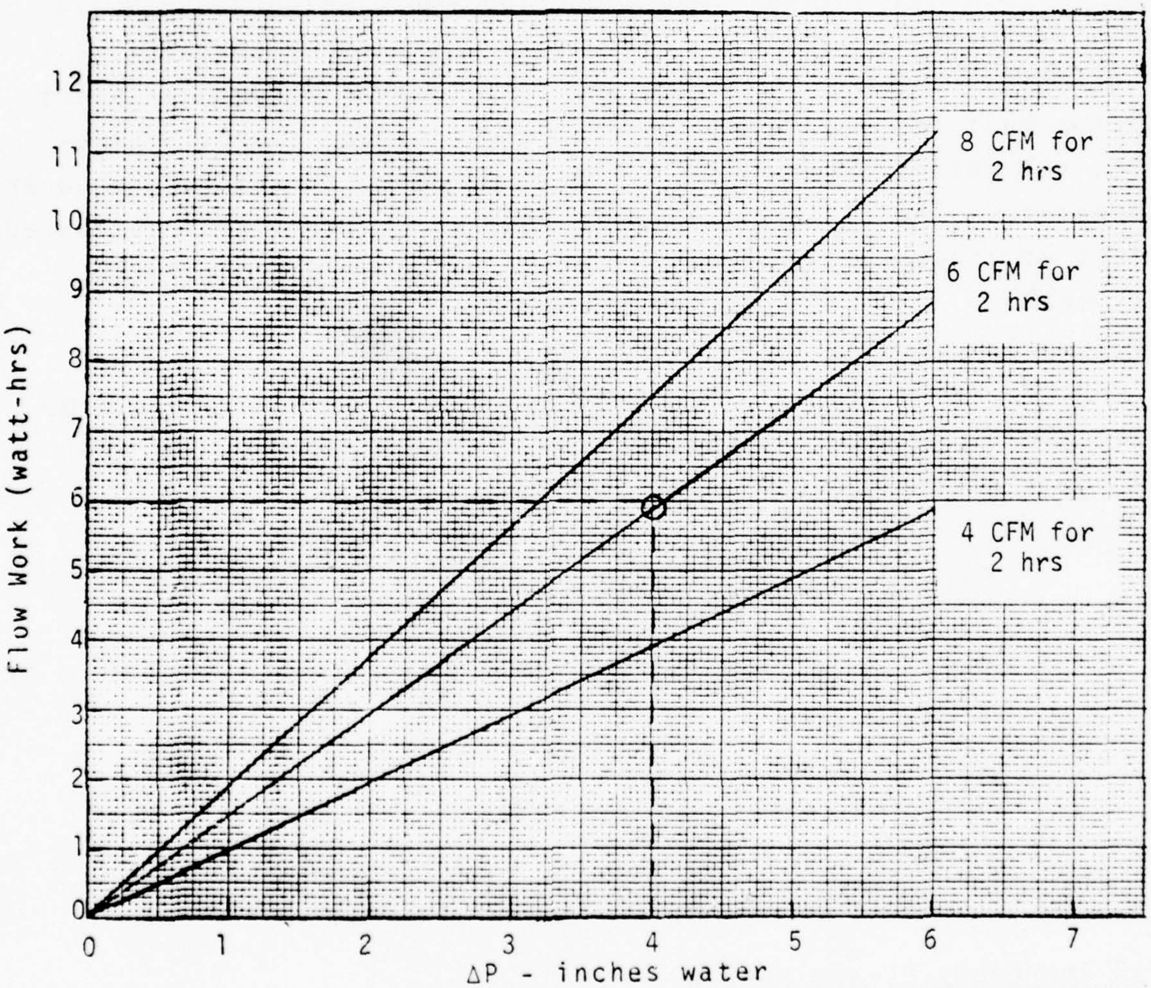


FIGURE 15. THEORETICAL FLOW WORK FOR TWO HOUR PERIOD

Using Ni-Cd batteries delivering 18 watt-hr per pound (See Figure 12), the battery weight is 1.50 lbs.

$$\text{battery weight} = \frac{27 \text{ watt-hr}}{18 \text{ watt-hr/lb}} = 1.50 \text{ lbs}$$

A blower delivering 6 cfm at 4 in. water head pressure would weigh about 3/4 lb.

Thus, a blower and batteries would weigh about 2 1/4 lbs. Estimated weight of a switch, wire and connectors is 1/4 lb or total of 2 1/2 lb. Reducing the breathing bag to an accummulator half the size would reduce weight by one pound. Therefore, net weight increase is 1 1/2 lb compared to the lung powered rebreather. The blower powered rebreather would have an estimated weight of about 18 1/2 lbs, not including added weight of the neck seal.

4.2.2 Cooling Module

Parts used in the "Cool Head" cooling module would be integrated into the ECU-2 backpack. Estimated weight for the cooling module components is 7 lbs.

Component	Wt (lbs)
Ice Canister, 1 liter	2.60
Batteries	1.50
Water Pump	0.50
Accummulator	0.40
Contact Heat Exchanger	0.50
Switches, bypass valves, etc.	0.50
Support, misc.	1.00
TOTAL	7.00 lb

4.2.3 Emergency Escape Module

A 45 cu ft air bottle is used for a 30-minute service time in an open circuit breathing apparatus. The emergency escape bottle can be incorporated into the ECU in several operational modes such as:

1. It can be designed as a self contained unit within the ECU, removed, then donned and arranged for use as an open circuit breathing apparatus as in the ECU-1 concept.
2. It can be piped in parallel to the primary breathing supply bottle, and arranged for operation as an open circuit breathing apparatus.
3. It can be piped in parallel with the primary breathing supply bottle, and arranged for operation to replace the primary O_2 supply bottle in the breathing apparatus.

In (1) and (2) above, the open circuit operation, O_2 supply required is about 7.5 cu ft based upon comparable O_2 supply requirements for commercial 30-minute open circuit breathing apparatus ($\frac{45\text{ cu ft}}{30\text{ min}} \times 5\text{ min} = 7.5\text{ cu ft}$). The supply bottle required would weigh about 4 lb.

In (3) above, the O_2 supply is economized and a smaller and lighter weight bottle is realized. This mode is selected on the basis of weight conservation and operational ease. For operation, personnel open the emergency O_2 bottle valve to admit the reserve O_2 supply. An ample reserve supply can be provided by a 2 3/8 in. diam x 6 in. long bottle weighing 1.63 lb. Pressurized at 2000 psig, O_2 storage is 32 liters (1.13 cu ft). If used at a rate of 4 LPM, supply time would be eight minutes.

Weight of the emergency escape module components is estimated to be 4.5 lbs.

Components	Weight (lb)
Bottle, 2 3/8 in. diam x 6 in. long	1.63
O_2 Supply	0.10
Bottle valve	1.00
Check valve, fittings	0.75
Bottle clamps, etc.	1.02
TOTAL	4.50 lb

4.2.4 Protective Case, Harnesses, etc.

Other components required for the ECU-2 include a protective case, harnesses for donning, structural members, miscellaneous hardware, latches, etc.

The estimated weight of these components is 7.5 lb.

Components	Weight (lb)
Protective case	4.0
Supports	2.0
Harnesses, buckles, etc.	1.5
TOTAL	7.5 lb

4.2.5 ECU-2 System Integration

The estimated weight of ECU-2 concept is 36 lb.

Components	Weight (lb) - Est.
Rebreather module	17.0
Cooling module	7.0
Emergency escape module	4.5
Protective case, harnesses, etc.	7.5
TOTAL	36.0 lb

The estimated weight is based upon a cooling module having a one liter ice canister. Replacement is required for a two hour operation period. Target weight for the ECU is 30-35 lb.

Figure 16 depicts ECU-2 concept configuration, a combined primary breathing supply, cooler and emergency breathing supply. ECU-2 would be integrated with the present POTMC suit.

The head/vest cooling garment is donned (flow circuit through the garment is shown in Figure 14.) Next, the protective suit is put on and then the ECU pack secured to the back of personnel by the adjustable harnesses.

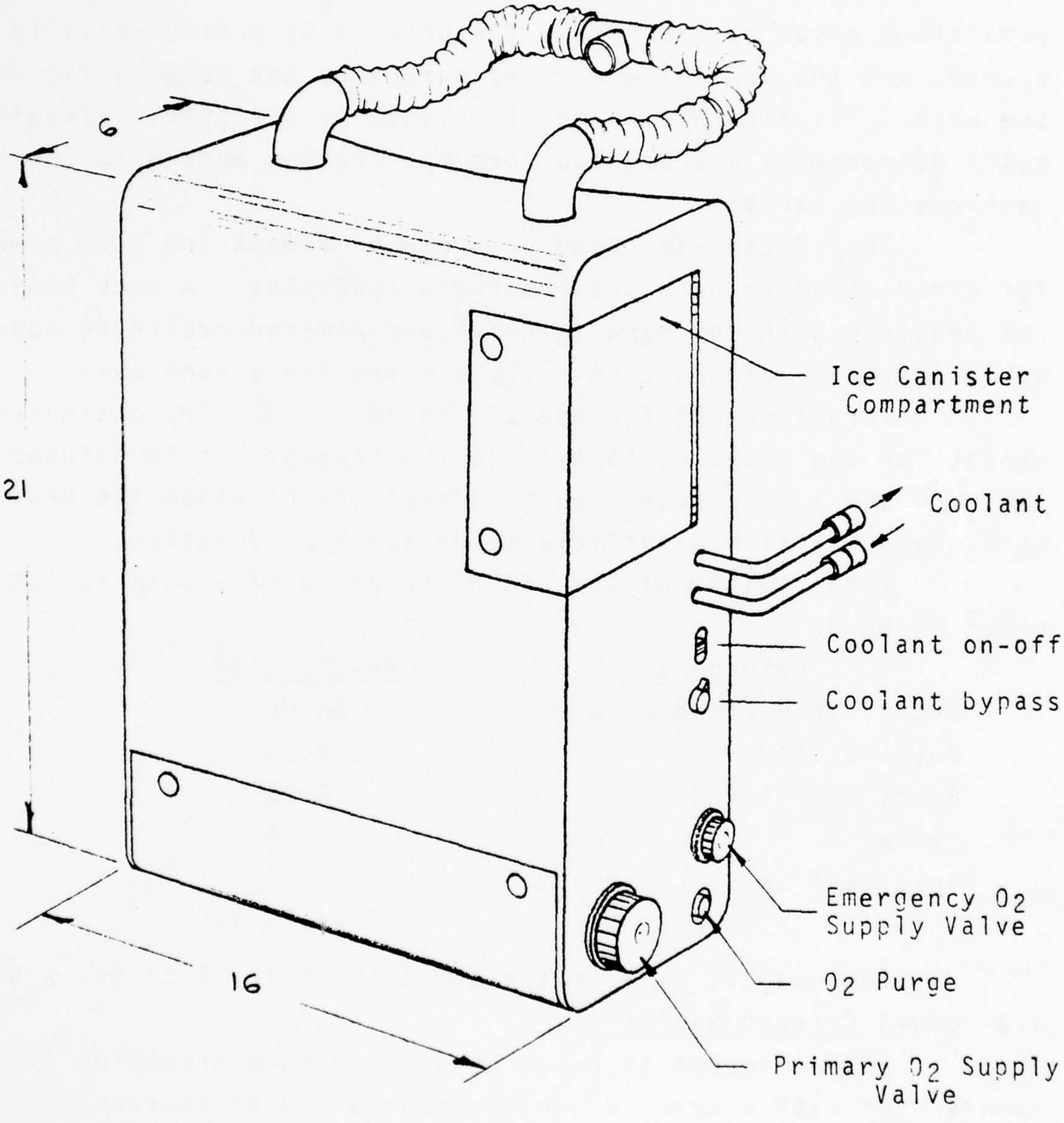


FIGURE 16. ECU-2 CONCEPT,
INTEGRATED UNIT

Breathing hoses extending from the breathing system are brought across the shoulders to the front. A flexible helmet with mask is attached to the suit neck ring. The mask is adjusted to the head with straps. A quick disconnect joins the inhalation-exhalation hoses to the mask. The primary O_2 bottle valve is opened, and the breathing circuit purged by the purge valve on the unit. The flexible helmet is closed by a zipper. Likewise, quick disconnects are used to form the cooling module to the head/vest cooling garment.

The concept is based upon use of a mask and lung power for circulation through the breathing apparatus. A neck seal is not required with the mask. The blower-powered breathing apparatus would increase weight, complexity and require a neck seal.

Target weight for the ECU is 30-35 lb. The estimated weight for the ECU-2 concept is 36 lb; however, it is pointed out that the ECU ice canister requires replacement since its heat removal capacity is not sufficient for a 2 hour duration.

Total weight of the ECU-2 and protective suit is estimated to be 57 3/4 lb.

Component	Weight (lb)
ECU-2, integrated mocule	36.00
Butyl suit	9.75
Boots and gloves	6.25
Helmet	3.75
Head/vest cooling garment	2.00
TOTAL	57.75 lb

The overall size of the ECU-2 is 16 in. x 21 in. x 6 in.

4.3 ECU-3 Concept Analysis

ECU-3 concept is based upon a separate breathing air module used with a mask, a cooling module and an emergency breathing module. A blower is used to filter ambient air through a chemical bed to remove contaminants. The filtered air is then passed through a composite layer undergarment as used with the POTMC protective suit for cooling.

Separation of the breathing and cooling supply would result in less stringent filtration requirements, since this air would be supplied for cooling and not as the breathing supply. Potentially, this concept increases the application range of a chemical filtration design approach in that only percutaneous contaminants become of concern since the breathing supply is a separate module.

4.3.1 Rebreather Module

The rebreather module used with this concept is the design used in ECU-1 and depicted in Figure 11. The estimated size of the rebreather module is 15 in. x 17 in. x 6 in. and a weight of 21 lbs. The module would be worn outside the protective suit, chest mounted and joined with hoses to a mask inside the protective helmet.

4.3.2 Cooling Module

The cooling principle for this concept is based upon filtered ambient air for cooling. Filtering contaminants out of the air by use of granular chemical beds will generated heat depending upon the contaminant and concentration level.

4.3.2.1 Chemical Canister

The filtering canister for this concept is based upon chemical granules of the type used in gas mask canisters. These include activated carbon for solvent vapor removal; caustic soda, or soda lime for acid contaminants; and a drier such as calcium chloride or activated alumina for water removal to protect the hopcalite bed from being poisoned. The hopcalite is used to oxidize contaminants such as CO to CO_2.

Based upon a filter cross sectional area of 0.33 sq ft (4 in. x 12 in. cross section) and a 1/4 second residence time in the activated carbon and hopcalite beds and a 1/8 second in the soda lime and drier bed, the following bed depth and charge weight of respective chemicals packed in the canister are as follows:

Chemical	Density (lb/cu.ft.)	Bed Depth (in.)	Weight (lbs.)	Particle Size Mesh
Activated Carbon	30	2.70	2.25	12-30
Soda Lime	50	1.35	1.87	6-14
Activated Alumina	58	1.35	2.18	4-6
Hopcalite	65	2.70	4.80	6-14
Totals		8.10 in.	11.10 lb	

The estimated pressure drop through the chemical bed at 18 CFM using an average particle size of 4-8 mesh is 1.3 in. water.

(7) $\Delta P = 1.67 \times 10^{-6} f \mu U = {}^{psi}/ft$ bed

where f = correlation factor plot of f vs A (Fig. 17)

$A = 0.0167\ G/\mu$

μ = viscosity, lb/hr-ft = 0.04 for air

G = mass velocity lb/hr. sq ft

U = Superficial linear velocity, ft/hr

W = mass flow rate, lb/hr

Flow rate - 18 cfm

Canister crossectional area = 0.333 sq ft (4 in. x 12 in.)

$$w = 18 \text{ cu. ft/min} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{0.075 \text{ lb}}{\text{cu.ft.air}} = 81 \text{ lb/hr}$$

G = W/Area = 81/0.333 = 243 lb/hr sq ft

A = 0.0167 x 243/0.04 = 101

from Figure 17, f = 330

$$U = \frac{18 \text{ cu. ft.}}{\text{min.}} \times \frac{60 \text{ min.}}{\text{hr}} \quad \frac{}{0.333 \text{ sq ft}} = 3243 \text{ ft/hr}$$

(7) Fluid Flow Through Packed Columns, S. Ergun. Chemical E. Progress, Vol. 48, No. 2, 1952

Step 1 Calculate A

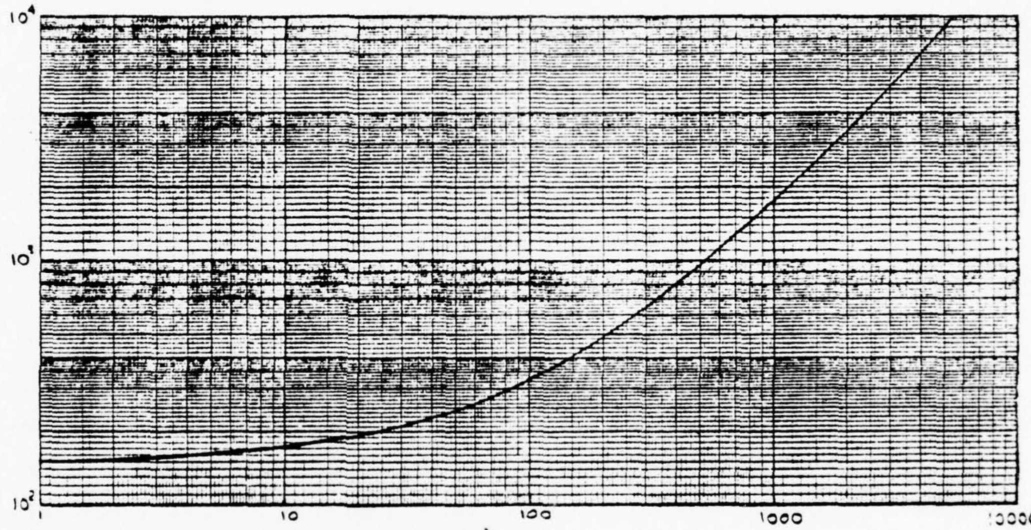
$A = 0.0100 \frac{G}{\mu}$ 8 x 12 mesh beads

$A = .0089 \frac{G}{\mu}$ 1/16 inch pellets

$A = .0167 \frac{G}{\mu}$ 4 x 8 mesh beads

$A = .0255 \frac{G}{\mu}$ 1/8 inch pellets

Step 2 For the determined value of A, read f from the graph.



Step 3 Calculate ΔP from following equations:

$\Delta P = \frac{\text{Pressure Drop}}{\text{foot of bed length}} = 3.86 \times 10^{-6}\, f \rho U \frac{\#}{in^2}$ (8 x 12 mesh)

$= 6.41 \times 10^{-6}\, f \rho U \frac{\#}{in^2}$ (1/16 inch)

$= 1.67 \times 10^{-5}\, f \rho U \frac{\#}{in^2}$ (4 x 8 mesh)

$= 1.57 \times 10^{-6}\, f \rho U \frac{\#}{in^2}$ (1/8 inch)

Notes:

G = mass velocity in $\frac{\#}{hr\ ft^2}$

μ = viscosity in $\frac{\#}{ft\ hr}$ = centipoise x 2.42

U = superficial linear velocity in $\frac{ft}{hr}$

FIGURE 17 - PRESSURE DROP THROUGH PACKED BEDS

$$\Delta P = 1.67 \times 10^{-6} \times 330 \times 0.04 \times 3243 = 0.0715\ ^{psi}/\text{ft bed}$$

$$\Delta P = 0.0715 \frac{\text{psi}}{\text{ft bed}} \frac{33.8}{14.7} \frac{\text{ft}}{\text{psi}} H_2O \times \frac{12 \text{ in.}}{\text{ft}} = 1.97 \frac{\text{in.water}}{\text{ft bed}}$$

for 8.1 in. long bed, the pressure drop is 1.33 in. water:

$$\Delta P = 1.97 \frac{\text{in water}}{\text{ft. bed}} \times \frac{8.1 \text{ in bed}}{12 \text{ in.}} \frac{\text{ft}}{} = 1.33 \text{ in. water}$$

Allowing for particulate filters and inlet and outlet flow losses, the overall pressure drop through the canister would be of the order of 1.5 in. water. Inlet and outlet plenums add length to the canister, allowing this to be about 1.9 in. the overall size of the filter canister would be approximately 4 in. deep x 12 in. wide x 10 in. long. Additional parts required for the canister are shell walls, bed separation screens and particulate filter media. An estimated weight of these parts is 2.4 lb, the weight of chemicals 11.1 lb; the contaminant removal canister has an estimated weight of 13.5 lb.

4.3.2.2 Heat Production

In the POTMC ECU, 18 CFM is passed through the filter for breathing and cooling. The multiplicity of contaminants and concentration levels would create a wide range of heat production levels. Considering carbon monoxide (CO) as a case example, about 800 BTU is produced by converting 1/4% (2500 ppm) CO to CO_2 at a flow of 18 CFM.

CO flow rate at 1/4% (2500 ppm) concentration is 0.203 lb/hr.

$$0.0025 \frac{\text{parts CO}}{\text{part air}} \times \frac{18 \text{ cu ft}}{\text{min}} \times \frac{0.075 \text{ lb air}}{\text{cu ft}} \times \frac{60 \text{ min}}{\text{hr}} =$$

$$0.203 \frac{\text{lb CO}}{\text{hr}} \text{ or } 3.283 \frac{\text{g-mol CO}}{\text{hr}}$$

Catalytic oxidation of CO to CO_2 and the heats of formation associated with the reaction are:

$$CO + 1/2\ O_2 \rightarrow CO_2$$

$$\Delta H\ (CO) = -26.416\ \text{k cal/mol}$$

$$\Delta H\ (CO_2) = -94.05\ \text{k cal/mol}$$

$$\Delta H\ (O_2) = 0$$

$$q = -94.05 + 26.416 = -67.634\ \text{k cal/mol}$$

$$q = 3.283\ \frac{\text{g-mol CO}}{\text{hr}} \times (-67.634)\ \frac{\text{k cal}}{\text{mol}} = -222.04\ \text{k cal/hr}$$

$$q = -222.04\ \frac{\text{k cal}}{\text{hr}} \times \frac{1000\ \text{cal}}{\text{k cal}} \times \frac{\text{cal}}{252\ \text{BTU}} = -881\ \text{BTU/hr}$$

For this case example, about 6.12 lb ice is required as a heat sink to remove the heat of reaction. The heat of fusion of ice is 144 BTU/lb ice:

$$\text{lb ice required} = \frac{881\ \text{BTU}}{\text{hr} \times 144}\ \frac{\text{lb ice}}{\text{BTU}} = 6.12\ \frac{\text{lb ice}}{\text{hr}}$$

Calculated adsorptive capacity[a] and temperature rise of the XM-41 carbon filter challenged by various saturated contaminants shows temperature rises indicated heat production levels larger than the above case example. For the heat production case and an air flow of 18 CFM, a temperature rise of 45F would result. Therefore it is necessary that a heat sink be provided to remove heat generated if ambient air is used for cooling.

4.3.2.3 Heat Sink

Based upon a heat production of 881 BTU/hr, the temperature rise in 18 CFM air is about 45F.

(a) A Study of the Effectiveness of XM-41 Filter for Use With Hazardous Chemicals, A.J. Juhola and J.V. Friel, Report CG-D-72-77, December 1977, p 51.

$$q = w\ C_p\ dt$$

$$q = 881\ \text{BTU/hr}$$

$$C_p = 0.24\ \text{CTU/lb °F (air)}$$

$$w = 81\ \text{lb/hr (air)}$$

$$dt = \frac{q}{wC_p} = \frac{881}{81\ (.24)} = 45.3°F$$

Thus, if air enters at 70°F it will exit at 115°F which would render the air flow ineffective, becoming a heater and not a cooler. A heat exchanger containing 6.12 lb ice as a heat sink is required to remove 881 BTU. The average temperature of air in the heat exchanger is 93°F ($\frac{70+115}{2} \cong 93°F$). Allowing for heat transfer film temperature drop and assuming the water-ice side of the heat exchanger wall at 42°F, the average temperature drop, ΔT, between the two fluids is 51°F (93°F-42°F = 51°F). Using a forced convection heat transfer coefficient, h_a for air of 5 BTU/hr-sq ft°F and a heat transfer coefficient, h_w, for water of 15 BTU/hr-sq ft°F, the overall heat transfer coefficient, U, for the heat exchanger is 3.75 BTU/hr-sq ft°F.

$$U = \frac{1}{1/h_a + 1/h_w} = \frac{1}{1/5 + 1/15} = 3.75\ \text{BTU/hr-sq ft°F}$$

Heat exchanger area, A, in sq ft is:

$$A = \frac{q}{U\Delta T} = \frac{881}{3.75(51)} = 4.61\ \text{sq ft}$$

The volume of 6.1 lb ice is about 0.10 cu ft (172.8 cu in.). For a 4 in. x 12 in. cross section, the thickness of a 6.1 lb ice block is about 3 3/4 in. Allowing half the volume of ice for air passages and separator plates the length of the exchanger is 4 in. x 12 in. x 5 3/8 in. and weight of the exchanger and water is 11 lb (6.1 lb water + 4 1/2 lb container).

4.3.2.4 Blower and Battery

The blower weight is estimated to be 2 lb. Battery weight to power the blower at 12 volts DC at 2.5 amps for two hours

is estimated to be about 5 lb. Total weight of blower and batteries is 7 lb.

4.3.2.5 Cooler Module Summary

The overall size of the cooling module is estimated to be 5 in. x 14 in. x 20 in. and have a weight of 36 lb.

Component weights for the cooling module are:

Component	Weight (lb)
Filter Canister	13.5
Heat Exchanger	11.0
Blower Batteries	7.0
Protective Case	2.5
Harness, Supports, etc.	2.0
Total	36.0 lb

The estimated weight of this cooling module concept is unacceptably high. Weight would be even greater if a 1/2 second residence time were allowed for the activated charcoal bed which is the design basis of the XM-41 filter. This would require an additional 2.25 lb activated carbon and add another 3-4 lb to the cooling module weight.

The XM-41 filter is designed so that 4 sq ft surface is available. This is accomplished by a pleated design but which results in a filter size of 3/4 in. x 12-1/4 in. x 13 in. containing 2.10 lb activated carbon and an overall weight of 6 lb.

4.3.3 ECU-3 Summary

The overall estimated weight of ECU-3 concept is 62-65 lb.

Component	Weight (lb)
Rebreather Module	21
Cooling Module	36
Emergency Escape Module	5-8
Total	62-65 lb

Since the target weight of the ECU is 30-35 lb, ECU-3 concept is considered not feasible.

Temperature rise that can be associated with contaminant filtering as pointed up in this concept analysis is a further shortcoming associated with the POTMC ECU as well.

4.4 ECU-4 Concept Analysis

ECU-4 concept is based upon filtered ambient air for breathing, an ice canister module for cooling, an emergency escape breathing apparatus, each separate, individual modules.

The breathing module contains a canister which filters inhaled air, exhaled air being expelled back to the ambient atmosphere. Since the breathing air source is the ambient atmosphere, this concept could not be used in an O_2 deficient atmosphere.

The cooling module is an ice canister through which water circulates and passes on to a head/vest undergarment for cooling.

An emergency escape module is the third component in the concept. The integration of the three modules constitues the ECU-4 concept.

4.4.1 Breathing Module

Components for the breathing module are a chemical canister, an inhalation hose, a mask and an inhalation-exhalation check valve manifold. The inhalation breathing hose extends from canister outlet to the helmet and to a mask inside the helmet. Exhaled gas is then vented back to the ambient air by means of an inhalation-exhalation valve manifold. The breathing module requires that ambient air has a normal O_2 concentration of 21% and would not be used in an atmosphere of O_2 concentration below 19.5%.

The heart of the breathing module is the chemical canister. The canister contains activated carbon which removes condensible vapors primarily by chemical reaction. Since the activated carbon collects condensible vapors, noncondensible acid vapors must be removed; caustic soda or soda lime are in the canister to scrub acid type vapors. Hopcalite catalyst is contained in the canister to convert CO to CO_2. Condensible and

noncondensible gases may be present at one time and in varying concentrations. All reactions are exothermic and heat production can become excessive increasing inhalation gas temperatures to unacceptable levels. An inhalation gas temperature of 110°F is about the maximum bearable.

4.4.1.1 Chemical Canister

Assessment of contaminant concentration must be made to ascertain the ability of the canister to remove the contaminant (with accompanying heat production). For instance, if CO is present in concentrations of 1/4% (2500 ppm), temperature rise is of the order of 45°F. If ambient temperature is 80°F, the inhalation temperature rises to 125°F. Heat of reaction associated with conversion of CO to CO_2 by catalytic oxidation with hopcalite was discussed in the ECU-3 concept. Temperature rises as a function of CO concentration level is as follows:

CO Concentration ppm	(%)	Temperature Rise (°F)*
100	0.01	1.8
500	0.05	9.1
1000	0.10	18.1
2000	0.20	36.3
2500	0.25	45.3

*Temperature rise is a functioh of CO concentration. Heat production is a function of flow rate. In this concept, canister air flow rate is the breathing rate and would vary accordingly.

The XM-41 filter used in POTMC was evaluated[8] for contaminant removal effectiveness by the activated carbon bed. Figure 18 shows service time as a function of concentration for the XM-41 filter (inorganic acid vapors are not removed by the filter). Service time as a function of vapor concentrations interpolated from the plot are:

ACTIVATED CARBON DATA

Ref: <u>A Study of the Effectiveness of XM-41 Filter for Use With Hazardous Chemicals</u>, A.J. Juhola and J.V. Friel, Report CG-D-72-77, Dec. 1977, p. 51.

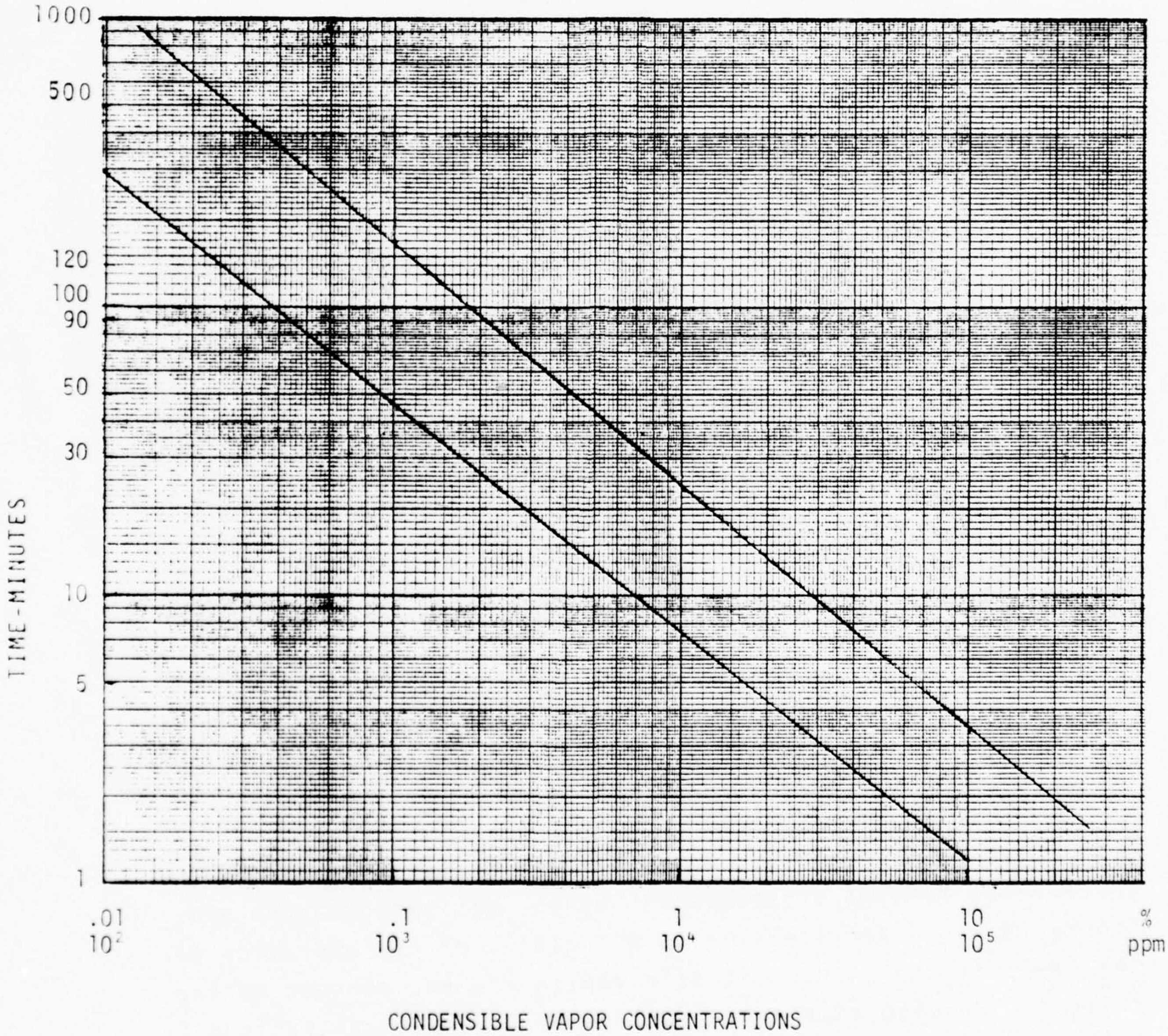


FIGURE 18. SERVICE TRACE BREAKTHROUGH TIME AS FUNCTION OF CONCENTRATION

Time	Vapor Concentrations (ppm)	(%)	(mm)
30	2630	0.263	2.00
60	790	0.079	0.60
90	500	0.050	0.38
120	330	0.033	0.25

From this study[8], heat production was estimated as a function of contaminant concentration. For seven typical contaminants, the heat production averaged about 365 cal/min-mm Hg (vapor pressure of contaminant). Based upon an air flow rate of 18 cfm or about 81 lb/hr through the XM-41 filter, the heat production rates related with contaminant concentration are:

Contaminant Concentration (ppm)	(mm)	81 lb/hr Air Flow Heat Production (cal/min)	(BTU/hr)	Air Temp. Rise (°F)
2630	2.00	730	174	9.0
790	0.60	219	51	2.6
500	0.38	139	33	1.7
330	0.25	91	22	1.1

In a breathing circuit, the lungs will move air at a lower mass flow rate. An estimate of air flow by breathing can be made from O_2 concentration change and O_2 consumption. Allowing a 2.8 cu ft O_2/hr usage rate, the lung air flow is 36.5 cu ft air/hr.

$$\text{Lung air flow rate} = \frac{2.8 \text{ cu ft/hr}}{0.210 - 0.133} = 36.5 \text{ cu ft/hr}$$

$$\text{Lund air mass flow rate} = 36.5 \text{ cu ft/hr} \times \frac{0.075 \text{ lb air}}{\text{cu ft}} = 2.74 \text{ lb air/hr}$$

In the chemical canister, the activated carbon will be exposed to lower flow rates and heat production would be correspondingly lower; however, temperature rise is a function of contaminant concentration.

Contaminant Concentration (ppm)	(mm)	2.7 lb/hr Air Flow Heat Production (cal/min)	(BTU/hr)	Air Temp. Rise (°F)
2630	2.00	24.7	5.8	8.9
790	0.60	7.4	1.8	2.7
500	0.38	4.7	1.1	1.7
330	0.25	3.0	0.7	1.1

Higher contaminant concentrations will produce higher heat production rates and temperature rises. On a pro-rata basis, a 25°F rise would be a contaminant concentration of 7380 ppm.

$$\text{ppm (25°F rise)} = \frac{25}{8.9} \times 2630 = 7380 \text{ ppm } (0.738\%)$$

Since the chemical canister in this concept is exposed to less contaminant flow, the service time of the activated carbon would be proportionate.

Contaminant Concentrations (ppm)	(%)	(mm)	Service Time - min. XM-41 Filter (81 lb/hr)	Chemical Canister Breathing Concept (2.74 lb/min)
7380	.738	5.60	7 1/2	222
2630	.263	2.00	30	887
790	.079	0.60	60	1773
500	.050	0.38	90	2660
300	.030	0.25	120	3547

An equivalent quantity of activated carbon, with the addition of other chemicals, would provide a greater degree of protection than in the XM-41 filter.

Selecting a canister size, 4 in. x 12 in. cross section, the amounts of chemicals and bed depth are estimated as follows:

<u>Activated Carbon</u>

Allow 0.53 second residence time

Bed cross sectional area = 0.333 sq ft

Average air flow rate = 36.5 cu ft/hr

Air flow velocity = 0.608 ft/sec

Breathing rate is sinusoidal, a peak instantaneous flow of 150 liters/min is the usual value used. The velocity at this peak rate is:

$$V = \frac{150 \text{ liters}}{\text{min} \times 28.3} \; \frac{\text{cu ft}}{\text{liter}} \times \frac{\text{min}}{60 \text{ sec}} \times \frac{1}{0.333 \text{ sq ft}} = 0.265 \text{ ft/sec}$$

About 2.2 lb activated carbon and a residence time of 0.53 sec are design parameters in the XM-41 filter. Bed depth in this canister concept is:

$$\text{bed depth, } L = \frac{2.2 \text{ lb carbon cu ft}}{30 \text{ lb carbon} \times 0.333 \text{ sq ft}} \times \frac{12 \text{ in.}}{\text{ft}} = 2.67 \text{ in.}$$

$$\text{residence time, } t = \frac{2.67 \text{ in.} \times \text{ft}}{0.265 \text{ ft/sec} \times 12 \text{ in.}} = 0.838 \text{ seconds}$$

Hopcalite bed catalytic oxidation of CO to CO_2 is based upon 0.25 second residence time.

$$\text{bed depth, } L = \frac{0.265 \text{ ft}}{\text{sec}} \times 0.25 \text{ sec} \times \frac{12 \text{ in.}}{\text{ft}} = 0.8 \text{ in.}$$

Allowing a one inch bed depth for the hopcalite, the quantity of hopcalite is:

$$\text{wt hopcalite} = \frac{1}{12 \text{ in.}} \times \text{ft} \times 0.33 \text{ sq ft} \times \frac{65 \text{ lb hopcalite}}{\text{cu ft}} = 1.8 \text{ lb}$$

A drier is used to remove moisture which poisons the hopcalite. The estimated water loading from air saturated at 80°F and volume of air breathed during two hours (73 cu ft) is:

$$\text{wt of air} = \frac{73 \text{ cu ft}}{359 \text{ cu ft}} \times 29 \text{ lb air} = 5.9 \text{ lb air}$$

The specific humidity at 80°F saturated (26.2 mm Hg) is:

$$\text{S.H.} = \frac{18}{29} \left(\frac{26.2}{760 - 26.2}\right) = 0.0222 \text{ lb water/lb air}$$

The water loading is:

$$\text{lb water} = \frac{0.0222 \text{ lb water}}{\text{lb air}} \times 5.9 \text{ lb air} = 0.131 \text{ lb}$$

Moisture removal based upon adsorption capacity of 4% requires 3.31 lb activated alumina.

$$\text{activated alumina} = \frac{0.131 \text{ lb water}}{0.04 \text{ lb water}} \times \text{lb alumina} = 3.3 \text{ lb}$$

Bed length of 3.3 lb activated alumina is 2.38 in.

$$\text{bed length, } L = \frac{3.3 \text{ lb alumina} \times \text{cu ft}}{50 \text{ lb alumina} \times 0.333 \text{ sq ft}} \times \frac{12 \text{ in.}}{\text{ft}} = 2.38 \text{ in.}$$

Allowing 0.5 sec residence time in the soda lime bed, the quantity and bed length are:

$$\text{lbs soda lime} = \frac{0.265 \text{ ft}}{\text{sec}} \times 0.5 \text{ sec} \times 0.333 \text{ sq ft} \times$$

$$\frac{50 \text{ lb soda lime}}{\text{cu ft}} = 2.2 \text{ lb}$$

$$\text{bed length} = \frac{2.2 \text{ lb soda lime} \times \text{cu ft}}{50 \text{ lb soda lime} \times 0.333 \text{ sq ft}} \times \frac{12 \text{ in.}}{\text{ft}} = 1.6 \text{ in.}$$

Weights and bed length for the canister chemicals are:

Chemical	Weight (lb)	Bed Length (in.)	Particle Size (mesh)
Activated carbon	2.2	2.67	12-30
Soda Lime	2.2	1.60	6-14
Activated Alumina	3.3	2.38	4-6
Hopcalite	1.8	1.00	6-14
TOTAL	9.5	7.65	

The estimated overall size of the chemical canister is 4 in. x 12 in. x 9 in. long. Weight estimate for the canister is 12 lb.

Component	Weight (lb)
Chemicals	9.5
Canister, shell	2.5
Screens, filters	0.3
TOTAL	12.3 lb

Summarizing, the overall weight of the breathing module is 14 lb.

Components	Weight (lb)
Chemical Canister	12.3
Breathing Hose	0.25
Manifold	0.25
Supports, disconnect	0.50
Harness	1.00
TOTAL	14.3 lb

4.4.2 Cooling Module

The cooling module is the same as given for ECU-1 and is shown in Figure 13. It has a weight of 9 lb and envelope dimensions of 8 in. x 10 in. x 3 in. Ice canisters are replaceable in the unit. Replacement is required to maintain metabolic cooling for a two hour period. This can be accomplished without interrupting the water coolant flow in the head/vest undergarment.

4.4.3 Emergency Escape Module

The emergency escape module is the type proposed for ECU-1 concept. It has an estimated weight of 5-8 lb and envelope dimensions of 3 in. x 8 in. x 9 in.

4.4.4 ECU-4 System Integration

The three components discussed for ECU-4 concept are the breathing (chemical canister), cooler and emergency escape modules. Integrated with the POTMC protective suit, they constitute the ECU-4 concept.

Ambient air must not be deficient in O_2, since this concept is based upon filtering air and does not supply O_2 from a bottled source as do the other concepts.

The head/vest cooling garment is donned, then the protective suit. The cooling module is attached to the back with a belt. Tubing from the cooling module is joined to the tubing leading into the suit to the head/vest garment by means of quick disconnects.

The breathing module is attached to the chest with appropriate harness. A quick disconnect on a breathing hose mates with the inhalation-exhalation manifold which in turn joins to the

mask. After mounting the mask, the helmet is secured to the protective suit ring seal. With the breathing module, inhalation air is drawn from the outside and through the canister which purifies the air. Upon exhalation, the inhalation valve closes, diverting expired air through the check valve back to the outside to complete an open flow circuit breathing system.

The emergency escape module is donned on the hip. A breathing hose from the emergency escape module connects into the inhalation-exhalation valve assembly. When the emergency escape module is needed, such as if the outside air becomes deficient in O_2, the valve on the emergency supply air bottle is opened and a diverter valve required on the chemical breathing canister is closed. Likewise, inhalation-exhalation gases pass into and out of the mask in an open flow circuit system as with the breathing module.

Estimated weight for this ECU concept is 28-31 lbs.

Component	Weight (lb)
Breathing Module	14
Cooling Module	9
Emergency Escape Module	5-8
TOTAL	28-31 lb

Combining the ECU with protective suit, helmet and head/vest undergarment, the overall weight is 49-3/4 - 52-3/4 lb.

Component	Weight (lb)
ECU-4	28-31
Protective Suit	9 3/4
Boots and Gloves	6 1/4
Helmet	3 3/4
Head/Vest Garment	2
TOTAL	49-3/4 - 52-3/4 lb

Controls for ECU-4 include an O_2 sensor and a toxic substance sensor. The O_2 sensor monitors outside ambient air.

The toxic sensor monitors gas quality exiting the chemical canister of the breathing module.

4.5 Equipment Concepts

In view of utilizing the POTMC protective suit, a neck seal and a flexible helmet have been considered on the basis of how they might be integrated into the ensemble.

4.5.1 Neck Seal

A neck seal was advanced as a concept in the ECU to isolate the helmet zone from the suit zone. Figure 19 illustrates a neck seal fashioned like a turtle neck. The butyl rubber suit material is sandwiched between an inner and outer metal ring and secured by screws. Likewise, the rubber neck seal is inserted between the two rings to secure it to the garment, thereby utilizing the POTMC protective suit.

4.5.2 Flexible Helmet

The rigid protective POTMC helmet makes donning of a mask inside the helmet impractical if breathing hoses enter through the helmet as suggested in the ECU concepts. If breathing hose entry were through the suit, the mask can be donned, straps adjusted to achieve a mask-face seal and then secure the helmet. A flexible helmet concept is shown in Figure 20. The mask is bonded to a flexible rubber hood having a zipper for a seal, the same type zipper seal as used on the suit. The mask with hood head cover is joined to the same metal ring used for the rigid helmet. This ring mates with the POTMC protective suit ring. In the use sequence the flexible helmet is placed over the head, the mask placed over the face, and straps adjusted through the entry provided by the zippered opening. The neck rings are connected and the zipper closed after hooking up with the breathing supply.

Since the suit neck ring is retained, a commonality exists for using the rigid helmet with the POTMC ECU if mission assignment permits its use or the ECU concepts considered in this analysis.

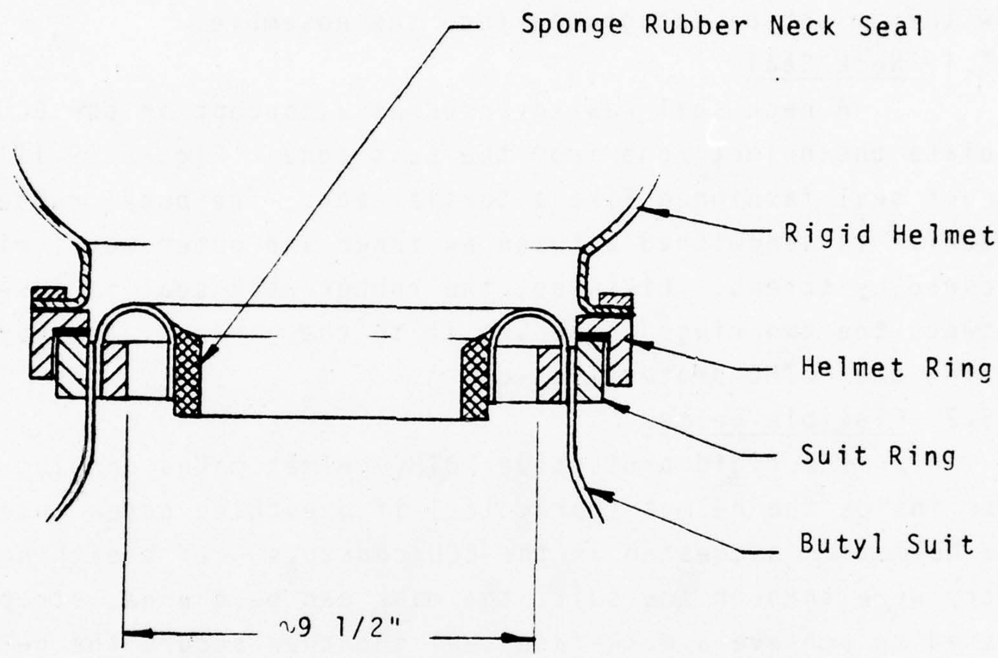


FIGURE 19. NECK SEAL CONCEPT

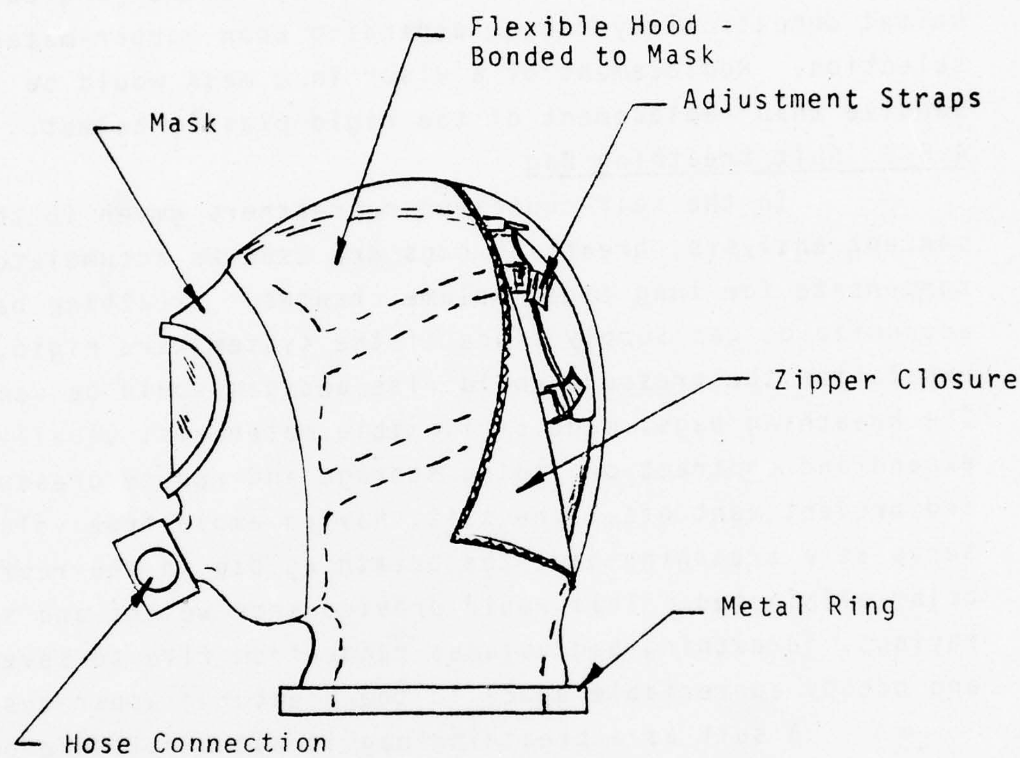


FIGURE 20. FLEXIBLE HELMET CONCEPT

Of the 900 hazardous chemicals given for the Coast Guard to be prepared to handle, about 600 are compatible with the butyl suit; the rigid helmet being compatible with only 325. The flexible mask-hood helmet may further increase the helmet compatibility range, depending upon rubber-material selection. Replacement of a visor in a mask would be less expensive than replacement of the rigid plastic helmet.

4.5.3 Suit Breathing Bag

In the self-contained rebreathers given in the ECU concept analysis, breathing bags are used as accumulators to compensate for lung tidal volume changes. Breathing bags economize on gas supply since if the system were rigid, upon exhalation the pressure would rise and gas would be vented off. The breathing bags, made of flexible materials, usually rubber, expand and contract providing storage and reduce pressure rises and prevent vent off. The suit, having ample free volume, could serve as a breathing bag; the breathing bag in the rebreather being eliminated. This would provide some weight and space savings. Breathing bag volumes range from five to seven liters and occupy appreciable space in the breathing apparatus.

A suit as a breathing bag is not a failsafe design if the suit is torn.

5.0 R&D INFORMATION

Information on concepts discussed in previous sections is presented in the following. Applicability of existing equipment will substantially reduce cost and man year effort.

5.1 ECU-1 Concept

ECU-1 concept consists of three modules having the following weights and sizes.

Modules	Weight (lb)	Size (in.)
Rebreather	21	15 x 17 x 6
Cooler	9	8 x 10 x 3
Emergency Escape	5-8	3 x 8 x 9
TOTAL	35-38 lb	

5.1.1 Rebreather Module

A required characteristic of the rebreather is that it provide a positive pressure.

Development of a two hour rebreather is considered on the basis of three possibilities.

1. Design entirely new rebreather for two hour service.
2. Modify commercially available two hour rebreather.
3. Modify commercially available 3/4 - one hour rebreather so that field refurbishment can be implemented to have two hour duration.

Of the above, (2) and (3) will require the lesser funds and man years of development. On the basis of weight conservation, (3) is favored.

Man years and funding for development are:

Rebreather Items	Man-yrs	Development Cost $ Time	Material	Total
(1) Develop new unit	3.0	162,000	15,000	177,000
(2) Modify existing 2 hour unit	1.0	54,000	2,000	56,000
(3) Modify existing 3/4 to 1 hour unit	1.0	54,000	2,000	56,000

5.1.2 Cooler Module

The cooler module proposed for ECU-1 concept is an ice canister "Cool Head" pack which is commercially available. Field refurbishing is planned to extend service time. Development required is modification to the protective suit for entry of coolant lines. No extensive development costs are involved. Current cost of the "Cool Head" pack and head/vest garment is $3,500. Man years and development cost to integrate the cooling module with the POTMC suit is estimated to be

Item	Man-yrs	Development Cost $ Time	Material	Total
Cooler Module	0.1	4,500	200	4,700

A longer duration cooling module will result in larger development cost and increase size and weight of the module accordingly. Development cost of a larger cooling module is estimated to be

Item	Man-yrs	Development Cost $ Time	Material	Total
Larger Cooler Module	0.5	27,000	1,400	28,400

5.1.3 Emergency Escape Module

A commercially available emergency escape device would be adapted accordingly. Man years and development cost are estimated to be

Item	Development			
		Cost $		
	Man-yrs	Time	Material	Total
Emergency Escape Module	0.1	4,500	100	4,600

5.2 ECU-2 Concept

ECU-2 is a single pack containing breathing, cooling, and emergency escape subsystems. The estimated weight is 36 lb and the size is 16 in. x 21 in. x 6 in. for ECU-2. This ECU concept requires more "grass root" design consideration and necessarily involves more man years and development cost. Implementation of this concept into field service will also be longer than the ECU-1. The estimated man years and development costs are estimated to be

Item	Development			
		Cost $		
	Man-yrs	Time	Material	Total
ECU-2, Integrated System	3.0	162,000	25,000	187,000

5.3 ECU-3 Concept

ECU-3 is considered as unsuitable; therefore, no man year effort or development costs are projected.

5.4 ECU-4 Concept

ECU-4 concept is based upon a filter air breathing module, a cooling module and an emergency escape module. Weight and size of each of these single modules are as follows.

Modules	Weight (lb)	Size (in.)
Breathing	14.0	4 x 12 x 9
Cooler	9.0	8 x 10 x 3
Emergency Escape	5-8	3 x 8 x 9
TOTAL	28-31 lb	

5.4.1 Breathing Module

The breathing module consists of a chemical canister for scrubbing contaminants from ambient air. It is not operable in an O_2 deficient atmosphere.

Estimated man years and development cost for the breathing module is

Item	Development			
		Cost $		
	Man-yrs	Time	Material	Total
Breathing Module	1.0	54,000	10,000	64,000

5.4.2 Cooler Module

The cooler module is the same as proposed for ECU-1 concept. Man years estimated is 0.1 years and development cost is $4,700 .

5.4.3 Emergency Escape Module

The emergency escape module is the same as given for ECU-1. Man years estimate is 0.1 years and development cost is $4,600.

5.5 Neck Seal

A neck seal was considered in the ECU concepts; however, a mask was found to be required in ECU-1 and ECU-2 since lung circulation flow rate was not adequate for CO_2 control in the helmet. A neck seal was required in ECU-3, but evaluation of this concept showed it to be unsuitable. Therefore, no man year and development costs are estimated.

5.6 Flexible Helmet

A flexible helmet with zipper seal has been discussed to facilitate use of a mask in the breathing systems. The flexible helmet will be designed to mate with the metal ring on the POTMC protective suit. Man years and development costs for the flexible helmet concept are as follows.

Item	Development			
		Cost $		
	Man-yrs	Time	Material	Total
Flexible Helmet	0.3	13,500	2,000	15,500

5.7 Major Milestones

Milestones associated with the development of the ECU are:

1. Prepare design specifications for ECU ensemble demonstration.
2. Evaluate contract bids - award contract development work.
3. Conduct design review.
4. Conduct critical design review.
5. Fabricate prototype ECU.
6. Demonstrate ECU ensemble.
7. Revise prototype ECU as required.
8. Prepare operational,support and maintenance information.
9. Specify equipment for field service support.
10. Procure ECU's and support equipment for field service use.
11. Issue ECU's for field service.

5.8 Potential Problem Areas

State of the art for breathing apparatus is well established. Breathing apparatus are used and maintained on a regular basis throughout the world. Application with a fully encapsulating suit is a potential problem area since less operational information is known. Common complaints are most likely to be weight, body movement restriction and comfort.

To conserve weight and gas storage, a rebreather principle was selected. However, operation with a face mask will be somewhat more uncomfortable with the rebreather than with an open circuit breathing apparatus. This is because in a closed flow circuit breathing apparatus, a CO_2 sorber canister generate heat. This heat tends to be retained in the apparatus. A continuous purge will be helpful to minimize a heat problem in the mask area. A 6.8 cu ft O_2 bottle will supply metabolic O_2 requirements. Continuous purging can be obtained by providing a bottle of the same weight (but about 2-1/2 in. longer) as a 6.8 cu ft O_2 bottle and delivering twice the volume of O_2 at an equivalent pressurization. A bottle of this type is a

composite fiberglass-aluminum bottle. These bottles are more recent developments, being fabricated at tooling costs of $36,000 and, consequently, less available than standard steel bottles. This could be a potential problem area in the delivery schedule.

A potential problem area is fogging and outside air infiltration. These would be lessened by a continuous purge as discussed above.

Another potential problem may be in the use of pure O_2. For short two hour duration, no physiological problem is expected. Relation of activity level and frequency of use may bear further consideration. Although no adverse reports are known on use of O_2 equipment in fires or hazardous chemicals, it must be considered. Grades of O_2 and quality for breathing purposes must be recognized.

Adequate cooling of personnel is an area that requires work. Providing sufficient cooling for a complete two hour mission duration results in excessive weight, although replacement of ice canisters to conserve weight is not anticipated to be a problem. Water cooling with a head/vest cooling undergarment will cool only at the skull and thorax region, and not at the legs and arms. This may be a potential problem area and, since 40% of blood circulation is through the head and heat exchange is to the blood, the cooling of the blood is depended upon to maintain the arms and legs at a comfortable condition.

Other potential problem areas would relate to development of helmet concepts different from those presented and adaption of the POTMC suit to salvage it for further duty with the ECU concepts considered in this program.

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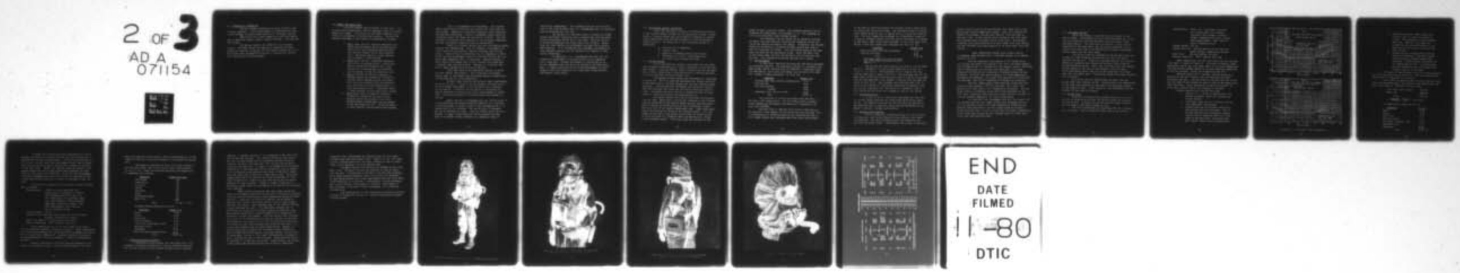


6.0 OPERATIONAL INFORMATION

The ECU concepts presented are based primarily upon a modular approach. Field refurbishment to extend mission time is the strategy to reduce weight which is an important concern.

Application of as much commercially available equipment as possible lessens logistic support problems - and none are anticipated.

ECU design concepts are simplistic and straightforward. Personnel should not require an extensive training program in learning to operate the life support system nor is it anticipated that incompatibility exists in maintaining the ECU with present Coast Guard equipment.

7.0 SUMMARY AND CONCLUSIONS

Four ECU concepts were evaluated in this study. All concepts were planned upon a modular approach, some to a greater degree than others. Utilization of the POTMC protective suit served as a guideline in evolving ECU concepts. The four ECU concepts evaluated in this study are summarized as follows:

1. ECU-1 Water Cooling; separate rebreather and water cooling modules donned outside the protective suit with breathing mask and head/vest cooling garment inside the protective suit. Rebreather module is chest mounted; cooling module is back mounted.
2. ECU-2 Water Cooling; integrated rebreather and cooling subsystems within a single pack donned outside the protective suit, back mounted with breathing mask and head/vest cooling garment inside the protective suit.
3. ECU-3 Filtered Air Cooling; separate rebreather module and chemically filtered air cooling modules donned outside the protective suit with breathing mask and composite layer ventilation cooling undergarment inside the protective suit. Rebreather module is chest mounted, cooling module back mounted.
4. ECU-4 Water Cooling; separate chemically filtered air breathing and water cooled modules outside the protective suit with breathing mask and head/vest cooling garment inside the protective suit. Breathing module is chest mounted; cooling module back mounted.

ECU-1 is recommended for development. This concept offers operational flexibility and requires the least time for development. Commercially available components can be obtained and modified accordingly. Modular arrangement lowers weight of individual parts, but there are more parts to handle. This ECU concept is considered to be operable by the personnel themselves and does not require buddy assistance as would ECU-2.

ECU-2 is a single, heavier pack but with modular design features for refurbishing. With all concepts, replacement supplies consist of gas bottles, chemical canisters and ice canisters. State of the art technology for all components in ECU-2 exists but more development effort is required than for ECU-1 to design the components into a single pack. Buddy assistance is more likely to be needed than in ECU-1 because the single pack is heavier than individual packs. Because it is heavier, the pack is best designed to be placed on the back.

ECU-3 was found to be impractical because of weight and heat removal requirements. ECU-4 requires a breathable oxygen level in the ambient and low enough ambient contamination to keep down the air inlet temperature.

No ECU's were found by the survey to meet requirements set forth in Task I. Analysis of ECU concepts concluded that a 30-35 lb weight requirement is not achievable for a two-hour service period. A two-hour service period is achievable by a modular approach and relying upon field refurbishment to extend time. The primary obstacle in meeting weight requirements is cooling.

Water cooling is recommended over air cooling since it is more effective and reduces sweating compared to air cooling. Circulating water is cooled through a heat exchanger which is in contact with an ice canister. The ice canister is reuseable and can be refrozen for reuse. Logistic support would not be a problem. A water cooled head/vest cooling garment provides about 4 lb weight savings compared to a composite layer air

ventilation undergarment. Heat exchange area may not be sufficient in the cooling module and it is recommended that its effectiveness be evaluated for this duty.

The concept of a face mask within a protective helmet affords additional protection over a conventional self-contained breathing apparatus having only a face mask. State of the art of breathing apparatus has proven them to be reliable. Guidelines for their design and performance have been set by government agencies. It is recommended that equipment procurement be from reputable concerns who are versed in all aspects of life support technology.

In conclusion, it is recommended that ECU-1 be considered for development as the best choice for an immediate short range plan. Further development in cooling may be required, depending upon evaluation of presently available equipment. A longer range plan would include development of ECU-2. Feedback from field operation will contribute to modification improvement in ECU design.

8.0 PRELIMINARY CONCEPT EVALUATION

Task V was revised to include a preliminary evaluation of the flexible helmet concept and cooling module concept. Prototyping a flexible helmet and cooling module hardware was investigated subjectively with the HCPCO (PTOMC-U.S. Army designation) protective suit. The objective of this investigation was to demonstrate:

a. Form and fit of headpiece
b. Comfort level
c. Behavior of ensemble during suit flexing
d. Performance of cooler, take temperature of cooler outlet stream with time.

8.1 Flexible Helmet

A full facepiece was unable to be donned with the HCPCO rigid fishbowl helmet because of space limitations inside the fishbowl helmet. A flexible helmet, used in conjunction with the metal ring of HCPCO rigid helmet is desirable since it becomes possible to utilize the HCPCO protective butyl suit.

A prototype flexible helmet was fabricated as illustrated in Figure 20. The first approach considered was bonding the mask to the hood cover at surfaces between the lens and adjusting strap locations. A second approach considered was mating the flexible hood with the mask lens clamp and inhalation-exhalation manifold clamp. The second approach requires no bonding of mask and hood materials, the joining being achieved mechanically.

The second approach was used to fabricate the prototype flexible hood. Mechanically joining the facepiece to the flexible hood was preferred to the bonding method because associated movement in donning and doffing would be more troublesome in maintaining a seal if the bonding method were used. Three ounce butyl rubber was selected to fabricate the flexible helmet. A 17 inch zipper on the back of the helmet was provided for access to don an MSA Ultra-View full facepiece which was mechanically joined to the prototype helmet. Sufficient space was provided in the

helmet to wear a hard hat inside. The prototype helmet with full facepiece and HCPCO metal ring weighed 2.4 lb. This compares to 3.75 lb for the HCPCO rigid fishbowl helmet.

The prototype flexible helmet can be donned by placing the metal ring over head and adjusting the facepiece straps utilizing the opening provided by the zipper. Preferably, the flexible helmet can be donned by inverting the hood through the ring so that the facepiece is outside. This facilitates mounting the facepiece and securing the adjustment straps. Next, the metal ring is positioned under the chin and the metal ring pulled back over the head. This procedure eliminates the need for a zipper.

8.2 Cooling Module

A "Cool Head" apparatus was procured from Acurex-Aerotherm for evaluation testing. The apparatus consists of a portable cool head system; mobile configuration P/N 3950-050, a head/vest liner, P/N 3950-200-01, and cooling cartridges (ice canisters) P/N 3950-019. Weight of these components is 10.64 lbs.

Component	Weight (lb)
Portable Cool Head, Mobile Configuration	5.16
Belt and Pad	0.67
Cooling Cartridge	2.61
Subtotal	8.44
Head/Vest Liner (fluid filled)	2.20
Total	10.64 lb

Two varieties of cooling cartridges were obtained, a 25°F and a 10°F freeze point. The 10°F freeze point provides a larger temperature difference and therefore is reported to improve heat exchange.

Duration time is reported to be one hour when wearing the head/vest liner garment and two hours with only the head liner. In consideration of extending duration and improving cooling, a jury rigged contact heat exchanger made from brass sheet shaped

to the cooling cartridge contour was mounted inside a metal pouch to receive the cooling cartridge. Two canisters piped in parallel would double duration time; in series would increase heat transfer rate. The jury rigged heat exchanger was subsequently found not to have as intimate contact with the cooling cartridge as provided by the fabric made contact heat exchanger in the "Cool Head" pack. Weight of the jury rigged heat exchanger pack was 6.37 lbs.

Component	Weight (lb)
Metal container with heat exchanger*	3.76
Cooling cartridge	2.61
Total	6.37 lbs

*Estimated weight of a plastic pouch and fabric heat exchanger would be about 1 lb.

The cooling cartridge contains one liter or 2.2 lb water and is a rectangular tin can having dimensions of 6 3/4 in. x 4 1/2 in. x 2 3/8 in. Heat exchange area in contact with the cooling cartridge is about 0.38 sq ft. Heat exchange area for the head liner is 0.60 sq ft and the vest liner is 2.02 sq ft and total area for the head/vest liner garment is contact with the body surfaces is 2.62 sq ft. Heat transfer rate from the head liner is given to be a maximum of 150 BTU/hr regardless of metabolic rate and for the head/vest liner 200 BTU/hr at a metabolic rate of 0.67 LPM O_2 and 500 BTU/hr at a metabolic rate of 1.67 LPM O_2.

8.3 Rebreather Module

In lieu of using a bottled O_2 rebreather for test mock up, an MSA Chemox apparatus was substituted which weighs about 15 lbs. The chemical canister was not utilized; the purpose of the apparatus was to simulate a chest mounted rebreather as proposed in the ECU-1 concept configuration.

8.4 Cooling Configurations

Prior to conducting subjective tests in a fully suited configuration, cooling performance of the portable "Cool Head" and head/vest liner were surveyed without the protective suit and other equipment donned. Thermometers were placed on the water

coolant lines in and out of the portable "Cool Head" pack to observe water coolant temperature change. Water flow through the garment first enters into the vest (thorax) liner and then to the head liner. A flow control valve located on the "Cool Head" pack adjusts water flow rate from 30 to 40 lb/hr. The counterclockwise valve stop position is 30 lb/hr water flow rate setting and the clockwise valve stop position is 40 lb/hr water flow rate setting.

Water temperature changes with various cooling arrangements were observed with a nonsuited subject at an ambient condition of 78°F.

With the head/vest liner donned, a 10°F freeze point ice canister and water flow setting of 40 lb/hr, the water temperature difference was 11°F indicating a heat removal rate of 440 BTU/hr. A 25°F freeze point ice canister also indicated a 11°F water temperature difference or no apparent difference between the two varieties. With only the vest on about a 5°F water temperature difference was observed. At a water flow setting of 30 lb/hr with the head/vest liner,an 8°F temperature difference was observed.

The jury rigged contact heat exchanger tested with the head/vest liner donned, a 10°F ice canister, and a water flow setting of 40 lb/hr gave a 3.6°F temperature difference. This was about a third as effective as the fabric heat exchanger in the "Cool Head" indicating less effective surface contact with the ice canister probably because of its rigid construction.

In a parallel flow arrangement with the "Cool Head" 10°F ice canister and the jury rigged contact heat exchanger having a 10°F ice canister, about a 6°F water temperature difference was observed indicating that a parallel piped system would nearly double duration time. In fully suited tests discussed subsequently, it was found that increasing heat exchange rates is a more beneficial goal than duration time.

8.5 Equipment Donning

About ten minutes is required with assistance to don the equipment. Retrofitting the suit with disconnects for liquid cooling connection with the head/vest liner would facilitate equipment donning. For preliminary evaluation, liquid cooling connection to the head/vest liner was done by removing a vent valve on the left side of the HCPCO suit for entry of the water cooling hoses from the "Cool Head".

The cooling vest was zippered on with the head liner off so that it could be passed through the suit neck ring while getting into the suit. After suit and boot donning, the flexible helmet and facepiece were donned and the head liner placed on top the facepiece straps. Next, the "Cool Head" pack was mounted on the outside of the suit on the subject's left hip area, quick disconnects being used to join the head/vest liner hoses with the "Cool Head" pack. Gloves were donned after chest mounting the rebreather.

An initial test was aborted when the head liner was placed under the facepiece straps. Coolant water flow construction in the head liner garment was noticeable from pressure exerted on the subject's head. Water leakage at the thermometer seal developed and the exercise stopped.

8.6 Suited Tests

Tests were conducted with subjects following a cycle of walking at three miles per hour for three minutes and standing for two minutes. A three mile per hour walking speed is equivalent to about a 1000 BTU/hr metabolic rate.

The first suited test was conducted with 155 lb subject for 70 minutes. Data collected for this test is as follows:

Configuration: HCPCO suit, "Cool Head" pack with 10°F freeze point ice canister, vest/head liner garment, flexible helmet, rebreather, tee shirt, shorts, socks, underclothes. Head liner on top of facepiece straps.

Subject Weight: 155 lbs

Subject Activity: Walking three miles per hour for three minutes, standing two minutes

Water Flow: Maximum setting, 40 lb/hr

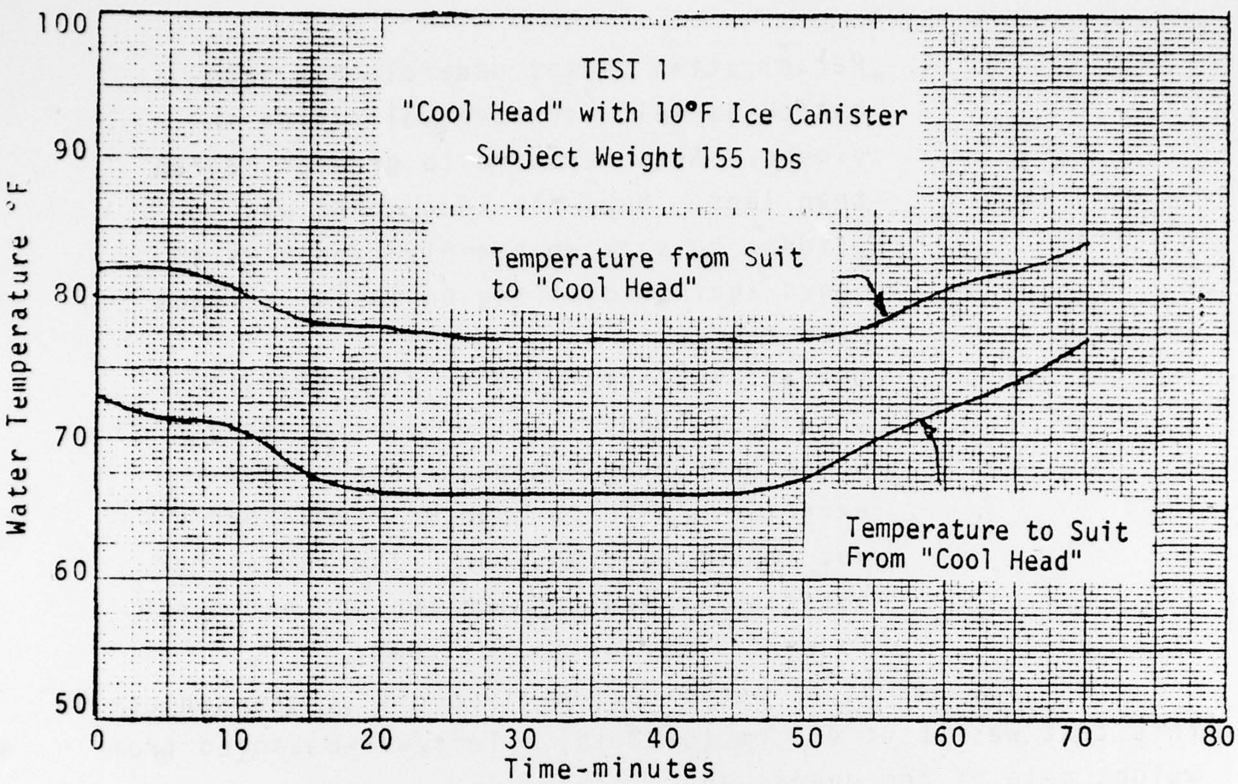
Ambient Conditions: 79°F, indoors, humid day

Water temperature into the "Cool Head" and out from the "Cool Head" is shown in Figure 21. At around 45 minutes, water temperature out of the "Cool Head" which is the water temperature into the cooling garment begins to increase denoting expenditure of the ice canister. Inside suit temperature was 91°F.

When the water flow is started, cooling sensation is apparent to the vest (thorax) area and remained noticeable throughout the test. Cooling effect to the head area was noticeable for about 15-20 minutes but less so than to the thorax area after that time. Water temperature to the suit was 66°F for 45 minutes at which time it was observed to increase.

General observations from the test were:

1. Subject is in a state of perspiration from donning equipment (humid day contributing to this effect).
2. "Cool Head" does not chill subject; cooling flow immediately appreciated.
3. Subject continues to perspire inside suit even though cooling is provided. This is because metabolic heat production exceeds cooling rate of apparatus which is of the order of 450-500 BTU/hr, additional body heat removal takes place by perspiration.



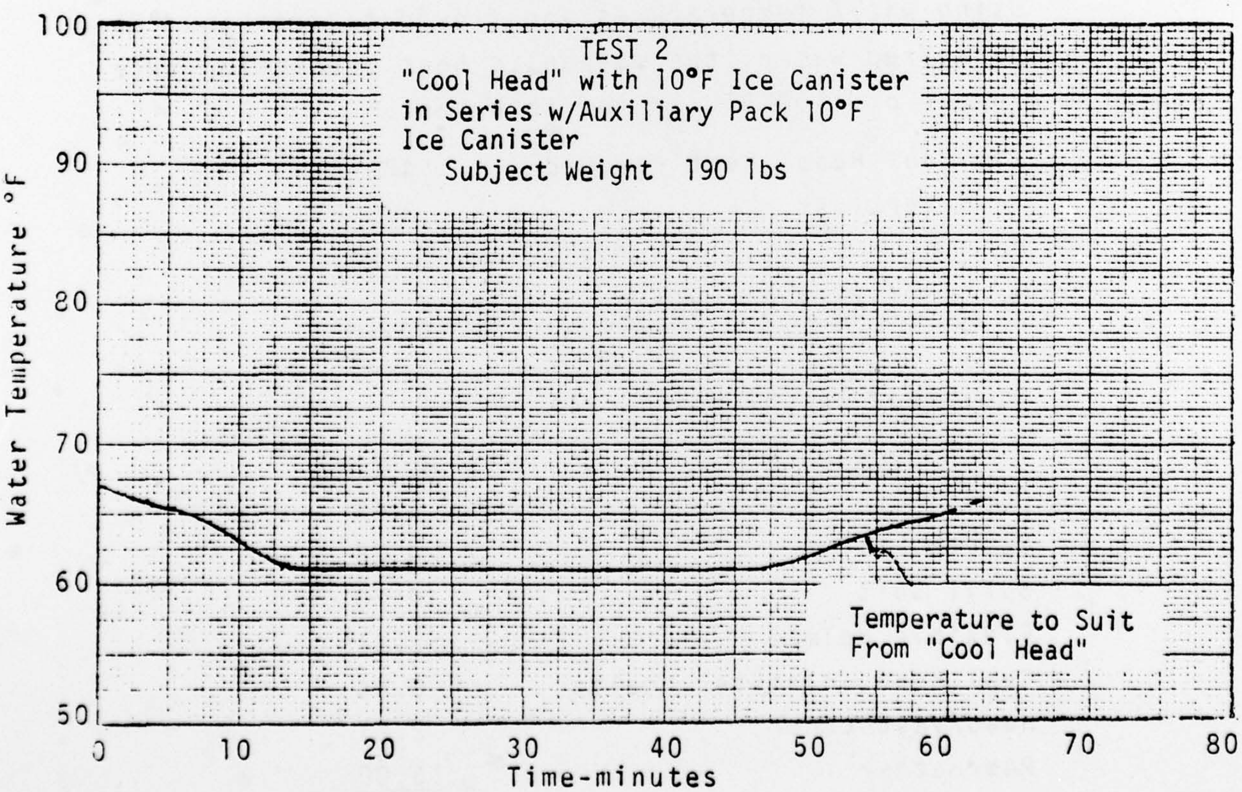


Figure 21 - "Cool Head" Water Temperature

4. Perspiration causes underclothes saturation as well as water collection in gloves. Arms perspire to greater degree than legs. Need for long johns was evident to soak up perspiration plus to guard against chaffing on inside of legs from the suit.
5. Subject was not fatigued from activity. Cooling is beneficial otherwise subject would have been fatigued sooner from exercise. A chest mounted rebreather did not impede bending over. The rebreather position tended to make the subject hunch forward later on in the test.

The amount of perspiration given off by the subject in this test was about 400 gm (0.88 lb). This was measured from weight gain of components and clothing.

Using water temperatures and flow data from the "Cool Head" and perspired water, the metabolic heat production rate was of the order of 1100 BTU/hr for this test.

"Cool Head" heat removed	425 BTU
Water loss	880 BTU
Total	1305 BTU

$$q = \frac{1305\ \text{BTU}}{70\ \text{min}} \times \frac{60\ \text{min}}{\text{hr}} = 1118\ \text{BTU/hr}$$

Equipment weight donned was 44 lbs.

Component	Wt (lb)
Boots	5.48
Gloves	0.78
Butyl Suit	9.70
Flexible Helmet	2.41
Cool Head, canister, belt	8.44
Head/vest Liner	2.21
Rebreather	15.00
Total	44.02 lbs

A second fully suited test was conducted with a 190 lb subject also walking at three miles per hour for three minutes and standing for two minute periods. This test was conducted for 60 minutes. In this test, the jury rigged contact heat exchanger with ice canister was piped in series with a second ice canister in the "Cool Head". Water flow from the head/vest garment first passed through the jury rigged contact heat exchanger and then into the "Cool Head" heat exchanger. With this flow arrangement, inlet water temperature to the suit was 61°F as compared to 66°F in the previous test with only a single ice canister in the "Cool Head".

This test was conducted for 60 minutes and the following data collected:

Configuration: HCPCO suit, Cool Head with 10°F freeze point ice canister in series with prototype auxiliary pack and 10°F freeze point ice canister. Head/vest liner garment, flexible helmet, rebreather, tee shirt, shorts, long john underclothes, head liner on top of facepiece straps.

Subject Weight: 190 lbs

Subject Activity: Walking three miles per hour for three minutes, standing two minutes

Water Flow Setting: Maximum setting, 40 lbs/hr

Ambient Conditions: 79°F, indoors, humid day

Water temperature out of the "Cool Head" which enters into the head/vest garment is shown in Figure 21. Water temperature to the head/vest garment with the series piped arrangement was about 61°F and again water temperature rise began around 45 minutes denoting expenditure of the ice canisters. Inside suit temperature was 95°F.

General observations from this test were essentially the same as in the previous test. Cooling effectiveness of the "Cool

Head" was observed by the subject, who had experienced use of the composite layer air ventilation garment, to be essentially equivalent.

The amount of perspiration given off by the subject in this test was higher than in the previous test; approximately 773 gm (1.7 lb). Water perspired was measured from weight gain of components and clothing:

Component	Weight Gain (gm)
Left glove	50
Right glove	55
Tee shirt	183
Shorts	58
Long johns	130
Socks	62
Vest/head garment	155
Butyl suit	80
Total	773 gm (1.7 lb)

Equipment weight donned was 50.4 lbs:

Component	Weight (lb)
Boots	5.48
Gloves	0.78
Butyl suit	9.70
Flexible helmet	2.41
"Cool Head" w/canister & belt	8.44
Head/vest liner	2.21
Rebreather	15.00
Auxiliary heat exchanger pack	6.37
Total	50.39 lbs

8.7 Prototype Evaluation Summary

A prototype flexible helmet was fabricated with a full facepiece; preliminary demonstration testing indicated that the form fit and function for this helmet concept to be a feasible

approach. A weight savings of 1.3 lb compared to the rigid fish-bowl helmet was obtained. The flexible helmet was best donned by inverting the helmet with the facepiece outside for entry, slipping the metal ring under the chin, and pulling the metal ring back over the head. A zipper is not needed with this method. Fabrication of the prototype flexible helmet was done by mechanically joining lens and breathing port areas to the butyl rubber hood and sewing and gluing butyl rubber seam joints. Vulcanized seamed joints would be required for field use helmets for leak tight construction. Sewed and glued fabrication did not permit checking for leak tightness. Rubber to rubber interfaces at mechanical joined areas are considered to be feasible for achieving leak tightness.

Water cooling provided by the "Cool Head" system performed to the degree specified for the unit in relation to capacity, rate and time as ascertained by water temperature change and flow rate data. Additional cooling sink capacity can be gotten by periodic ice canister replacement which is easily accomplished with the "Cool Head". Heat exchange rate of the order of 500 BTU/hr was indicated from data. A maximum heat exchange rate of 500 BTU/hr was found to be limiting inasmuch as metabolic rates were greater resulting in subjects perspiring to compensate for additional cooling rate needed. Since the contact heat exchanger area (0.38 sq ft) interfacing with the ice canister is balanced with head/vest liner area (2.62 sq ft) in contact with body area, an increase in both heat exchange areas would be required to increase heat exchange rate to reduce perspiration. However, in the one hour tests, subjects did not report undue fatigue but would unlikely be able to endure a two hour period. On the basis of these tests, the as is "Cool Head" configuration is judged to have a maximum use time of 45-60 minutes. Reconfiguration would be required for a two hour use period. Comparatively, the subject in the second test had experienced use of the air ventilated

composite layer undergarment and reported that the "Cool Head" provided about the same comfort level. Benefit of the "Cool Head" system is perhaps more fully realized, compared to the air ventilated cooling garment, in a high humidity area.

Equipment donning and operation are impeded by the rigid metal ring. The metal ring does not provide for ease of entry into the suit. Interference of the metal ring with the facepiece and a chest mounted rebreather makes it difficult for personnel to make manipulations such as belt adjustments with the "Cool Head". A desirable goal is to provide a configuration in which personnel have as much control of equipment as possible. Replacement of the rigid metal ring with a zipper arrangement is an alternate consideration.

The configuration for this preliminary evaluation testing is shown in Figures 22, 23 and 24. Figure 25 shows the prototype flexible helmet.

FIGURE 22 - FULLY SUITED CONFIGURATION FOR PRELIMINARY CONCEPT EVALUATION

FIGURE 23. FULLY SUITED CONFIGURATION FOR PRELIMINARY CONCEPT EVALUATION - FRONT VIEW CLOSE-UP

FIGURE 24. FULLY SUITED CONFIGURATION FOR PRELIMINARY CONCEPT EVALUATION - BACK VIEW CLOSE-UP

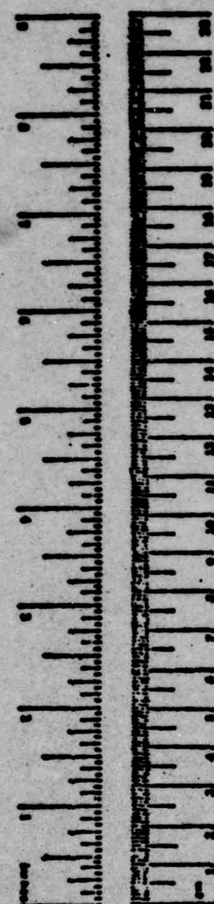
FIGURE 25. PROTOTYPE FLEXIBLE HELMET

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

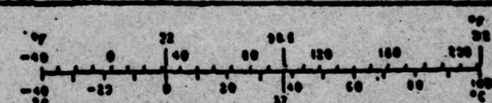
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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